Project	AtlantOS – 633211
Deliverable number	D1.7
Deliverable title	**Refined AtlantOS Requirements Report**
Description	Refined description from AtlantOS work of the societal imperatives for sustained Atlantic Ocean observations, the phenomena to observe, EOVs, and contributing observing networks.
Work Package number	WP1
Work Package title	Observing System Requirements and Design Studies
Lead beneficiary	IOC / UNESCO
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Comments	An extension was asked for (and granted) so that the AtlantOS Future Observing Network Design workshop could be held to discuss network plans and integration in light of OSSE results from Work Package 1.

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Stakeholder engagement <u>relating to this task</u>*

WHO are your most important stakeholders?	☐ Private company If yes, is it an SME ☐ or a large company ☐? x National governmental body x International organization ☐ NGO x others Please give the name(s) of the stakeholder(s): Understanding user needs will help optimise the observing system to better meet the requirements of national governments, international conventions, and users in industry.
WHERE is/are the company(ies) or organization(s) from?	☐ Your own country x Another country in the EU x Another country outside the EU Please name the country(ies): All national governments will benefit with a better ocean observing system, as will industry and other users from many countries.
Is this deliverable a success story? If yes, why? **If not, why?**	x Yes, because it outlines how user needs can be continually refined to improve the ocean observing system. ☐ No, because …..
Will this deliverable be used? **If yes, who will use it?** **If not, why will it not be used?**	x Yes, there are specific recommendations on how to improve the understanding of user needs and its impacts on network design for: observing networks, modellers, national governments, and ocean observing governance structures, including EOOS. ☐ No, because …..

NOTE: This information is being collected for the following purposes:

1. To make a list of all companies/organisations with which AtlantOS partners have had contact. This is important to demonstrate the extent of industry and public-sector collaboration in the obs community. Please note that we will only publish one aggregated list of companies and not mention specific partnerships.
2. To better report success stories from the AtlantOS community on how observing delivers concrete value to society.

*For ideas about relations with stakeholders you are invited to consult <u>D10.5</u> Best Practices in Stakeholder Engagement, Data Dissemination and Exploitation.

Refined AtlantOS Requirements Report

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Executive Summary

The AtlantOS project aimed to deliver an advanced framework for the development of an integrated Atlantic Ocean Observing System that goes beyond the state-of–the-art, and leaves a legacy of sustainability after the life of the project. To accomplish this, its 62 partners in 18 countries have examined how the entire ocean information value chain can be improved to more effectively and efficiently deliver ocean products and services. This document outlines the requirements for an integrated All-Atlantic Ocean Observing System, but they are equally applicable for other oceans, and, indeed, for a global ocean observing system.

Building a fit-for-purpose ocean information system first requires an understanding of what is meant by requirements. There are a wide variety of current and potential users for ocean products and services, including citizens wanting to spend the day at the beach, marine vessels hoping to reduce shipping costs, maritime industry aiming to increase operational safety at sea, managers and policy-makers wishing to improve the preservation of ecosystems and the services they provide, and the financial industry and first responder agencies dealing with extreme events such as hurricanes.

Coastal populations and infrastructure are growing and are increasingly exposed to ocean-related hazards, and marine industries and users continue to grow – ocean forecasts and early warning systems can help manage risk, improve business efficiency, and (through Marine Spatial Planning) allow different users to share the ocean space and resources effectively and with minimal harm to the environment.

These users require different ocean products and services, from (detailed or summarised) current conditions, often in real time, to short-term forecasts and long-term projections, to baseline monitoring, scientific process studies, and risk assessments. However, end-user needs are only one component of the requirements needed to build the ocean information value chain. Those who develop applications or use ocean data in numerical models have a different understanding of what is needed. There are also requirements from scientists seeking to understand how various components of the ocean system (e.g., upwelling) work and their impacts on ocean biogeochemistry, biology, and ecosystems, and from ocean observers themselves. Capturing and refining these requirements in the context of political trends, changing ocean states, new technologies, and emerging risks necessitates an ongoing dialogue with the wide-range of users, sensor and application developers, and observation experts, as well as systems such as the Framework for Ocean Observing, to organise and harmonise approaches and vocabulary.

Some parts of the ocean information value chain, such as high-level user requirements (e.g., arising from Sustainable Development Goals) where we largely know what we need to know and measure, impose requirements on the system from the top down. However, other parts of the system are more organic, and requirements are imposed from the bottom up. For example, best practices, data management, and the trade-off amongst individual observation programmes are a (geographic and/or expert) response to high-level needs; the best local and technological solutions in developing an ocean information value chain cannot always arise from central-planning, but rather from competition and the marketplace of ideas. Local priorities, for example, will always be an important factor in determining which observation programs are funded, and the governance system for an AtlantOS programme must be able to effectively coordinate a wide variety of solutions.

Partnerships between the institutions involved in the entire ocean information value chain (including observing, data management, analysis, and dissemination) are increasingly important as the needs for ocean information become more sophisticated (e.g., in ecosystem-based management approaches). Governance of the processes required to design, adapt, and optimise the ocean observing system and the interactions between the partners will be key for the future Atlantic Ocean Observing System.

The AtlantOS project examined each of these components, as well as their role in creating and sustaining an efficient fit-for-purpose ocean observing system. Many outputs from the AtlantOS project have provided

recommendations on how to improve various aspects of ocean observing, from data management to technology development to partnerships and governance.

The present study focuses on user needs: high-level requirements arising from operational services, Sustainable Development Goals, and other international agreements and conventions; evaluations of pilot projects and national surveys undertaken in AtlantOS; results from a capacity and gaps analysis and a cost and feasibility study; and results from a series of Observing System Evaluation (OSE) and Observing System Simulation Experiments (OSSE) trials.

At a Future Ocean Observing Design Workshop, AtlantOS synthesised these results, along with individual networks' future plans and strategic goals, to envision a future integrated and fit-for-purpose ocean observing system for the Atlantic Ocean. Respecting that funders (generally nation states, but also, increasingly, the private sector) are likely to continue to support certain observing networks to meet national or local needs (or for historical reasons), a number of recommendations are put forth to improve the entire ocean information value chain to meet the needs of society, industry, and the environment. These recommendations touch not only on individual networks, but also on the importance of capacity building and standards in promoting integration.

Recommendation 1: Establish a planned and systematic forum for dialogue between users of ocean information, observation program leaders, and sensor and application developers to understand evolving needs and capacities.

Goals

- Build a strong end-user community aware of the benefits of long-term ocean observations.
- Build a community of ocean observers aware of user needs so they can refine observation programmes to more efficiently and effectively provide the data needed. This includes better integration between the open-ocean and coastal observing communities, as well as between the physics, biogeochemistry, and biology / ecosystem communities.
- Build a community of sensor and technology developers who understand user needs and produce cost-effective monitoring solutions.
- Build a community of third-party application developers to transform ocean data into ocean products and information.

Activities

- GOOS should coordinate this activity internationally; the Physics, Biogeochemistry, and Biology/Ecosystem Panels are already working within the observing community to integrate cross disciplines (e.g., Essential Ocean Variables - EOVs).
- GOOS GRAs can be valuable in aiding integration between the open-ocean and coastal observation communities. While a number of GRAs are proving to be very effective (e.g., EuroGOOS, IOOS and IMOS), others could use GOOS further support.
- Pilot projects are one method to grow the community of users and application developers.
- GOOS can adopt a regular national survey approach, as piloted in AtlantOS, to understand national needs and priorities.

Recommendation 2: Establish a framework to regularly and systematically evaluate and optimise network design with numerical models (e.g., OSEs and OSSEs) and other analytic tools, including cost and feasibility studies.

Goals

- Identify key locations (e.g., gates or bottlenecks) in which to monitor.

- Prioritise observation requirements relevant to various goals of the observing system (e.g., for science process studies, reducing forecast error, or understanding phenomena and improving applications).
- Demonstrate the value of observations, which will aid in securing sustainable funding.
- Monitor how well the observing system is meeting observation requirements.

Activities
- GOOS and OceanPredict develop long-term strategy and yearly workplans to coordinate international OSE and OSSE simulations.
- Further develop network monitoring tools (such as those created at JCOMMOPS and EMODnet through the AtlantOS project), which include moving beyond platform-based measures to develop EOV- and phenomenon-based metrics.
- Standardise cost-accounting approaches and have GOOS incorporate cost estimates into its regular national survey approach.

Recommendation 3: Establish accessible, discoverable, and interoperable databases for data, metadata (including infrastructure, planned deployments, and current observing activity) and best practices.

Goals
- Ensure all observed data is free and open access, with compatible standards, and associated metadata on quality control, etc.
- Keep current inventories of costly and unique infrastructure and of upcoming deployments, to assist in infrastructure sharing and the development of future enhancements of observation networks.
- Collect an authoritative source of metadata on best practices to help new observation activities establish themselves more quickly and ensure that their data is compatible with the existing system.
- Make available, in near-real time, metadata on current observation activity (i.e., instruments in the water) to allow for monitoring and assessment of how well the observation system is meeting user needs.

Activities
- Resolve the data gap due to unavailable data by encouraging observers to properly fund data management and share data.
- Support efforts to develop, and encourage the use of, data tracking and citation protocols.
- Encourage observation networks to share metadata concerning their available and deployed infrastructure and platforms.
- Support the continued development and sharing of best practices.
- Host regular inter-network dialogue with JCOMMOPS and EMODnet to facilitate the creation and update of EOV- and phenomena-based performance metrics.

It is not possible to definitively describe user needs in a world with constantly-evolving ocean states, political priorities, and technological capacity. Rather, we have outlined a framework in which to consider user needs (the Framework for Ocean Observing[1]) and the processes and activities to continually update our understanding of the need for new and enhanced ocean information and improve the observing, data management, analysis, and dissemination components of the ocean information value chain. As we move from the AtlantOS project to the AtlantOS programme, partnerships and governance will be key to establishing an All-Atlantic Observing System responsive to the needs of all users.

[1] https://goosocean.org/index.php?option=com_content&view=article&id=18&Itemid=118

1 Introduction

Relevant, up-to-date, and integrated information is key to making rational, science-based decisions in a wide variety of fields in our modern world, from finance to agriculture to industry, as witnessed by the emergence of big data and cloud computing. The same is increasingly true in areas affected by the world's oceans, including fisheries and aquaculture, marine transport, renewable ocean energies, conservation, and even weather forecasting. For example, meteorological services around the world increasingly rely on ocean information to provide more accurate and longer-term forecasts.

The global meteorological community has worked together to develop an integrated data collection, data management and assimilation, numerical model, analysis, and communication system to enable nations to provide weather information and prediction services. For example, the Global Telecommunication System (GTS), a "co-ordinated global system of telecommunication facilities and arrangements for the rapid collection, exchange and distribution of observations and processed information," is a global facility with common standards and protocols, implemented and operated by National Meteorological Services, ensuring that they each have access to all meteorological and related data, forecasts and alerts. These services serve a broad range of users, including agriculture, industry, and citizens, ranging from information on current conditions to seasonal (and long-term climate) forecasts, and include alerts to mitigate loss of life and damage from extreme events.

The oceanographic community has a similar range of end-users, a similar suite of required information products and services, similar issues regarding the value of internationally sharing data arising from projects funded and managed at the regional or national level, and a similar need for common standards, best practices, and user engagement in defining and refining user needs. Unfortunately, while the meteorological community has already built up a truly integrated and effective system, the oceanographic community is only now in the process of holistically determining how to establish a truly efficient and fit-for-purpose value chain for ocean information.

There are several challenges in building a Global Ocean Observing System (GOOS). The oceanographic community needs to more regularly engage a wider swath of the user-community to better understand their needs. These products and services need to be understood in terms of the measurements that must be made; the observation programmes that must be refined, improved, created, and integrated; the data standards, best practices, management, and access that must be coordinated; the models and monitoring tools that need to be standardised to continuously assess performance; and the partnerships and governance systems that must be put in place to sustain the system.

The AtlantOS project, as described in this report, has made strides in each of these areas in the context of the Atlantic Ocean. Many of its deliverables have made recommendations on how to move forward in the AtlantOS programme – the AtlantOS High-Level Strategy[2] and the European Strategy for Atlantic Ocean Observing[3], in particular, outline needs for a future All-Atlantic Ocean Observing System. In general, the oceanographic community needs to better communicate the value of ocean information by effectively and efficiently fulfilling user needs. This will not only attract sustained funding to rectify the current reliance on sunsetting sources (75% of ocean observation programs are currently funded on short-term research projects, compared to 25% for the atmospheric community[4]), but will also generate use and interest among external stakeholders, establishing a cyclical process of improvements in products and services.

[2] http://www.atlantos-ocean.org/assets/files/AtlantOS_Brochure_v15_EN.pdf
[3] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D9.5.pdf
[4] https://insitu.copernicus.eu/library/reports/Sustainabilitysurveyupdatedreportfinal.pdf

2 Observation Requirements

There are multiple pathways into user requirements, through high-level societal benefit areas (for policy-makers and funders), through applications (for industry) and phenomena (for scientists), and through low-level Essential Ocean Variables (for observing networks). Understanding how these different types of requirements fit together, key to building an effective ocean observing system, is complex: a single high-level benefit may require several tools and applications, which may each need scientific understanding of multiple phenomena, each, in turn, necessitating the observation of many oceanographic variables. At the same time, each oceanographic variable contributes to the understanding of many phenomena, is important in developing multiple applications, and is required to meet objectives in quite a number of the high-level societal benefit areas. This interdependence of needs is clearly seen when these relationships are depicted graphically (Figure 1).

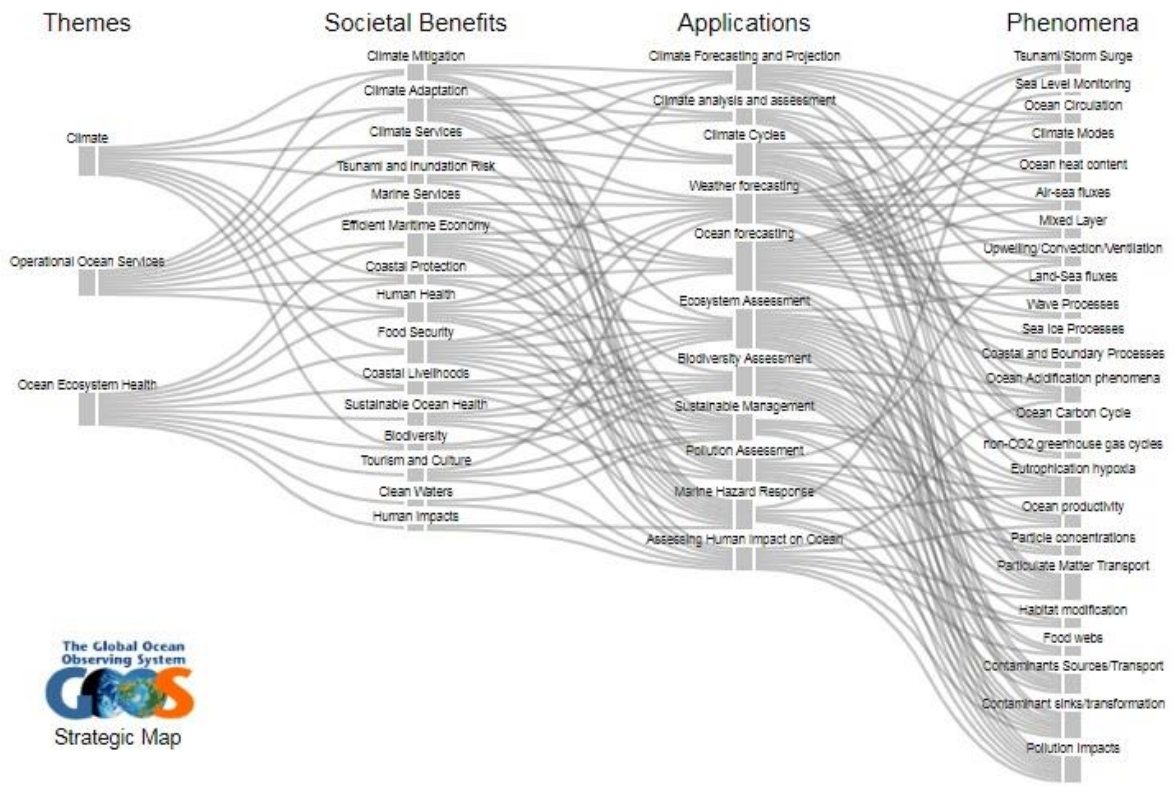

Figure 1: GOOS' Links between high- and low-level observation requirements[5]

2.1 High-Level Requirements

Many international organisations, agreements, and conventions outline how Earth Observation (EO) are needed to monitor conditions and support policy-making, management decisions, and enforcement. These individual benefits are often grouped together under common themes, foci, or benefit areas. For example, the World Meteorological Organization (WMO), the United Nations body responsible for international cooperation and coordination of national weather services, has seven focus areas[6] around which it organises its observations, modelling, and product development: energy, environment, natural hazards and disaster risk reduction, oceans, polar and high-mountain regions, public health, and urban development.

[5] https://www.goosocean.org/index.php?option=com_content&view=article&id=120&Itemid=277
[6] https://public.wmo.int/en/our-mandate/focus-areas

2.1.1 The Global Ocean Observing System

The Global Ocean Observing System is a sustained collaborative system of ocean observations, encompassing in situ networks, satellite systems, governments, UN agencies and individual scientists whose aim is to coordinate ocean observations to provide benefit for humanity in understanding, monitoring, and sustainably using the world's oceans, regional seas, and coastal waters.

GOOS has developed a Framework for Ocean Observing to guide its implementation of an integrated and sustained ocean observing system. This systems approach, designed to be flexible and to adapt to evolving scientific, technological and societal needs, helps deliver an ocean observing system with maximised user base and societal impact. Observation requirements are driven through a process of understanding which Essential Ocean Variables (EOVs, described in Section 2.3) are required to understand the applications and scientific knowledge underpinning these high-level needs. This same approach has been adopted by the AtlantOS project, and, indeed by the European Strategy for an AtlantOS[7] and the global AtlantOS High-Level Strategy (both outputs of the AtlantOS project) outlining an enhanced Atlantic Ocean Observing System that benefit all of us living, working, and relying on the Atlantic Ocean.

GOOS organises itself around, and implements its activities through 13 GOOS Regional Alliances (GRAs, Figure 2). The GRAs have different strategies and organise their work differently, in response to local and regional differences in scientific and societal priority, funding opportunities, capacity, and governance models. There are five existing GRAs working in the Atlantic Ocean: EuroGOOS (Europe), IOOS (U.S.), IOCARIBE GOOS (in the Caribbean Ocean), OCEATLAN (South America) and GOOS Africa. A sixth GRA, CIOOS, is being established in Canada. GRAs work together with the GOOS Secretariat (housed at the Intergovernmental Oceanographic Commission) to maintain and develop common strategies, standards, and best practices.

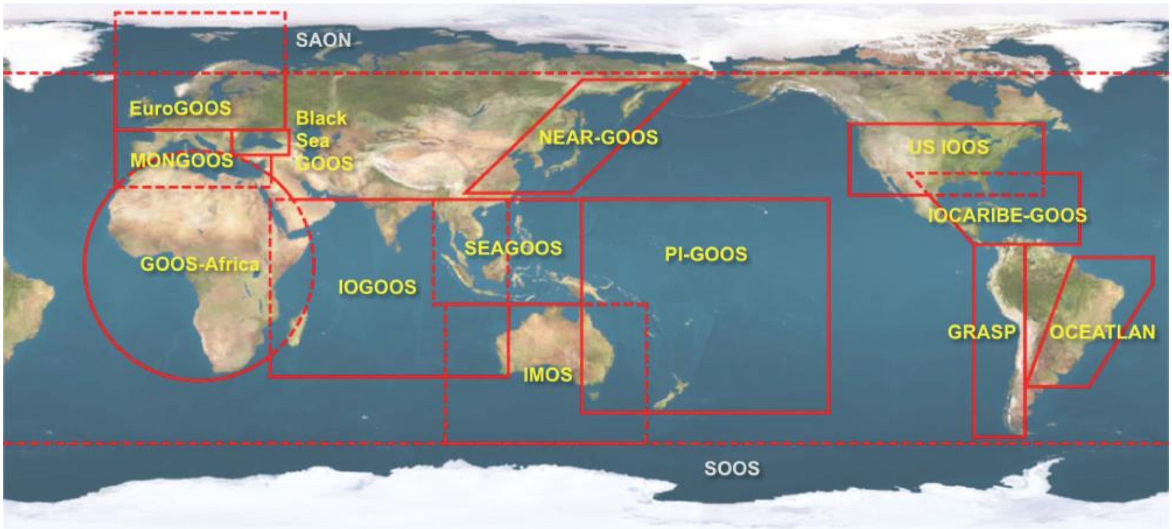

Figure 2: The GOOS Regional Alliances[8]

GOOS groups the socio-economic, cultural and environmental benefits of ocean observing under three main themes, each of which has been subject to a major international agreement or framework (described in Section 2.1.3) since 2015: Climate (the UNFCCC's Paris Agreement), Operational Ocean Services (the Sendai Framework for Disaster Risk Reduction 2015–2030), and Ocean Health (the UN Sustainable Development Goals).

[7] http://eurogoos.eu/download/project_deliverables/AtlantOS-D9.5.-European-Strategy-for-All-Atlantic-Ocean-Observing-System.pdf

[8] https://www.goosocean.org/index.php?option=com_content&view=article&id=83&Itemid=121

Climate

The global ocean is a key component of the climate system and influences its evolution and change through the energy, water, and carbon cycles. It has a profound and multidimensional influence on planetary conditions, interacting with Earth's atmosphere, cryosphere, land, and biosphere. It also directly influences human welfare through the provision and transport of food and resources, as well as by providing cultural and economic benefits, all of which will be deeply affected by climate change. Ocean information can help improve benefits in climate mitigation, climate adaptation and climate services.

Climate **mitigation** aims to reduce and minimise anthropogenic climate change and its direct impacts on the global oceans, including higher ocean temperatures, sea-level rise, and lower pH levels. These primary effects lead to secondary impacts, including altered patterns of precipitation and drought, increased hurricane and flooding activity, reduced biodiversity, and changes in fishery stocks and location. The oceans play a large role in mitigating climate change, taking up more than 90% of the excess heat from the heat imbalance due to the emission of greenhouse gases and acting as an important sink for excess carbon dioxide and other greenhouse gases. Monitoring the open and coastal oceans is needed to understand how the ability of the ocean to act as a buffer is being reduced and to determine the impacts on the ocean itself. For example, destruction of mangrove habitat, whether through sea-level rise or land-use decisions, reduces the ability of coastal ecosystems to store carbon and allows carbon already stored to affect the climate balance.

The level of anthropogenic greenhouse gasses in the atmosphere and the inertia of the climate system have committed human society to a century or more of climate change, even if greenhouse gas emissions were mitigated completely and immediately. Climate **adaptation** involves developing the tools and applications required to manage successful strategies for society to adapt to our already-changing environment and to adapt to economic losses (e.g., due to storms) and changes in economic activity (e.g., fisheries). There is increasing societal demand for more systematic and detailed information on how weather patterns, climate, sea level, ocean conditions and marine productivity are changing (mean and extremes), how they will change in the future (predictions/projections), and what is driving these changes (e.g., understanding of physical mechanisms and the role of human activities and other natural external and internal factors). For example, global patterns of excess rainfall and drought will be affected by changes in ocean circulation and temperature (impacting agriculture) and the ocean carbonate system is becoming more acidic (reducing ocean fish stocks and biodiversity). The shorter timescales of climate prediction required by adaptation will require better understanding of ocean processes, particularly in the Atlantic Ocean, as well as good monitoring of the ocean state in order to initialise coupled climate forecast systems.

Climate **services** provide climate information to assist decision-making by individuals and organisations. Such services require appropriate engagement along with an effective access mechanism and must respond to user needs. Such services involve high-quality data from national and international databases on temperature, rainfall, wind, soil moisture and ocean conditions, as well as maps, risk and vulnerability analyses, assessments, and long-term projections and scenarios. Depending on the user's needs, these data and information products may be combined with non-meteorological data, such as agricultural production, health trends, population distributions in high-risk areas, road and infrastructure maps for the delivery of goods, and other socioeconomic variables. The WMO Global Framework for Climate Services (GFCS), for example, provides planning, policy, and practice on climate change at global, regional, and national scales. Observations, including ocean observations that are needed for predictions on time scales from intra-seasonal to decadal time scales, are a pillar of the GFCS.

Operational Ocean Services

The oceans play an important and growing role in the international economy. The OECD (Organisation for Economic Co-operation and Development[9]) report The Ocean Economy in 2030[10] notes that ocean-related economic activity, conservatively estimated at USD 1.5 trillion in the present (with 31 million direct jobs in

[9] https://www.oecd.org/

[10] https://read.oecd-ilibrary.org/economics/the-ocean-economy-in-2030_9789264251724-en#page1

2010), is expanding rapidly. It states that "many ocean-based industries have the potential to outperform the growth of the global economy as a whole, both in terms of value added and employment." Economic value is predicted to exceed USD 3.0 trillion, with 40 million jobs; offshore wind energy, marine aquaculture, fish processing, and port activities are likely to experience the fastest growth. In addition to the range of economic activities which can overlap in time and space, there are also competing political, social, safety, and environmental concerns.

The focus on the business development of marine industries without compromising the vulnerable marine environment, security, and efficiency of operations puts strong demands on the availability of reliable operational meteorological and oceanographic products and services. These products and services are based on systematic and long-term routine measurements of the seas, oceans, and atmosphere, and the rapid interpretation and dissemination of data, information, and products. Important products include:

- **nowcasts** – relevant, timely, and accurate descriptions of present marine conditions including of living resources
- **forecasts** – continuous predictions of future conditions as far ahead as possible
- **hindcasts** – description of past states, and time series showing trends and changes
- **applications and tools** – including marine spatial planning tools to optimise competing uses of ocean resources and space, ship-routing applications to save fuel and reduce risk, and siting tools to optimise placement of aquaculture and ocean energy industry

The WMO describes the global needs for operational ocean services in its Rolling Review of Requirements, particularly in the Statement of Guidance for Ocean Applications. Marine Meteorology and Oceanography serve a wide range of users, from international shipping, fishing and other met-ocean activities on the high seas, to the various activities that take place in coastal and offshore areas and on the coast itself. These users demand analyses, synopses, forecasts, and warnings, which necessitates accurate, detailed, and timely (including, in some cases, real-time) knowledge of the present state of the atmosphere and ocean. These marine services include:

- managing tsunami and coastal inundation risk from storm surges
- marine services aimed at the safety of life and property at sea and in coastal areas
- sea ice services
- supporting an efficient maritime economy through ocean condition and forecasting services for shipping, marine industries, ocean structures, renewable energy applications, search and rescue, and defence operations

In the Atlantic Ocean, the American (IOOS) and European (EuroGOOS) GRAs are the most developed. As a result, operational observing activities are heavily concentrated in the northern hemisphere, primarily within the 200 nautical mile zone. Although there is some activity in the other GRAs, and also in the open ocean (Argo floats and the PIRATA tropical moored array), a comprehensive operational services program for the Atlantic Ocean will require more observations in the open ocean, and considerably more observational activity in the southern hemisphere.

The U.S. Integrated Ocean Observing System (**IOOS**), led by NOAA, is a national consortium of governmental and non-governmental stakeholders, with specific interest in marine environmental phenomena occurring in the open ocean, U.S. coastal waters, and the Great Lakes. Its core mission is to produce, integrate, and communicate high quality ocean, coastal and Great Lakes information that meets the safety, economic, and stewardship needs[11] of the United States. Seven areas of societal benefit drive the design and implementation of the IOOS program: ocean climate variability, safe and efficient marine operations, national security, sustained use of resources, healthy ecosystems, mitigation of natural hazards, and public health[12].

[11] https://ioos.noaa.gov/about/about-us/
[12] http://www.iooc.us/wp-content/uploads/2013/01/U.S.-IOOS-Summit-Report.pdf

The European Global Ocean Observing System (**EuroGOOS**) is an association of 44 members from 18 European countries focused on European-scale operational oceanography and ocean observing systems in the IOC / GOOS context. The EuroGOOS Strategy 2014-2020 centres around five areas: define operational oceanography strategies, promote operational oceanography, foster European and global cooperation, initiate co-production, and sustained ocean observing. EuroGOOS supports free and open data on portals such as the Copernicus Maritime Environmental System (CMEMS) and the European Marine Observation and Data Network (EMODnet). In cooperation with the European Marine Board, EuroGOOS has established the European Ocean Observing System (EOOS) to "align and integrate Europe's ocean observing capacity, promote a systematic and collaborative approach to collecting information on the state and variability of our seas (climate), and underpin sustainable management of the marine environment and its resources (ocean health).[13]"

Canada is in the process of establishing its integrated ocean observing system, **CIOOS**. While ocean observing activities in the Caribbean have been relatively few, the seven members of **IOCARIBE GOOS** have built an extensive network of tide gauges, mainly as part of a tsunami early warning system. **OCEATLAN** is an association of institutions from Brazil, Uruguay, and Argentina working in the southwest Atlantic – in addition to coastal observations, they participate in the PIRATA tropical moored array and in Argo floats. The coordination of ocean observing in Africa is still in the early stages, and most of the observing activities of the members of **IOCAFRICA-GOOS** are small and focused on the coastal regions. Each of these GRAs have an important role to play in a coordinated and integrated all-Atlantic Observing System, and they will require varying levels of engagement to foster the use of common standards and best practices. Governance (Section 3.6) will be key to ensuring observation and data integration across these different regions.

Ocean Health

Growing coastal populations and, as the world moves to a blue economy, increased marine activity will put more and more strain on the marine ecosystem. Half of the world's population live along or within 200 km of a coastline on just 10% of the earth's land area, a proportion that will only increase with further urbanization. Seaborne trade is expected to quadruple by 2050, and certain marine activities, such as mining and wind energy, more than double. Biotechnology, including new drugs, shows particular promise. Understanding marine ecosystems, minimising harm to ocean health and biodiversity, and ensuring the continued provision of ecosystem services will require improved governance and planning, for which ocean information is key.

The observation programs needed to properly manage and protect ocean health are much less developed than those that provide physical oceanographic data for traditional operational oceanography. For biogeochemistry, the Global Ocean Acidification Observation Network (GOA-ON) is fairly recent, and the BGC Argo program is still being rolled out. For biology and ecosystem science, the wider variety of data types and the amount and complexity of data needed to even establish baselines is considerably larger than for physics or biogeochemistry, and includes video, acoustics and DNA analysis, which is expensive and time-consuming. There have been considerable technological advances in recent years (e.g., the promise of lab-on-a-chip), which requires supporting observation and data standards and best practices. The biology and ecosystem approach to ocean information has been of a different focus than that of physics and biogeochemistry (e.g., pressures and drivers, as outlined in Section 2.1.3), but AtlantOS and GOOS has worked to coordinate an approach based on Essential Ocean Variables to enable further integration.

As our understanding of the ecosystem and of the potential biological benefits (e.g., ecosystem services and biotechnology) improves, our monitoring requirements will become clearer. This area, in particular, is one in which ongoing dialogue among users, scientists, and observation experts is needed to refine user requirements and ensure the observation system captures the ocean data to support it.

[13] http://www.eoos-ocean.eu/about/what-is-eoos/

2.1.2 Societal Benefit Areas

The Group on Earth Observations (GEO) defines Social Benefit Areas (SBAs) as domains in which Earth observations are translated into support for decision-making to benefit human health, economy, and the surrounding environment. In its Strategic Plan for 2016-2025[14], GEO defined eight SBAs (Table 1), each of which can benefit from relevant and timely ocean information. GEO considers Climate to be a cross-cutting Societal Benefit Area, impacting each of these SBAs.

Societal Benefit Area	Relevance to the Need for Ocean Information
biodiversity and ecosystem sustainability	• 90% of the habitable space on Earth • greater diversity in the oceans than on land
disaster resilience	• coastal populations are growing • the risk and severity of ocean hazards is growing
energy and mineral resources management	• ocean renewable energy is promising • ocean oil and gas is growing
food security and sustainable agriculture	• fisheries and mariculture are growing
infrastructure and transportation management	• 90% of global trade is through marine traffic
public health surveillance	• Harmful Algal Blooms and pollution affect health
sustainable urban development	• coastal populations and cities are growing
water resource management	• the oceans impact rainfall and drought patterns

Table 1: GEO Societal Benefit Areas and the need for ocean information[15]

2.1.3 Global Drivers

European nations, as well as many other nations bordering the Atlantic Ocean, have entered into a number of international agreements and accords seeking to benefit wider society by protecting the environment, reducing poverty, saving lives, and responsibly developing the ocean economy. Many of these agreements have specific goals and metrics, as well as reporting obligations, all of which require ocean observation to advance scientific understanding, set baselines, and understand trends.

Sustainable Development Goals

In 2015, the United Nations adopted 17 Sustainable Development Goals (SDGs) as part of its *2030 Agenda for Sustainable Development*. SDG 14[16] ("Conserve and sustainably use the oceans, seas and marine resources for sustainable development") comprises 10 targets, including:

- significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution
- sustainably manage and protect marine and coastal ecosystems
- minimise and address the impacts of ocean acidification
- effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans;
- conserve at least 10 per cent of coastal and marine areas
- sustainable management of fisheries, aquaculture and tourism
- increase scientific knowledge, develop research capacity and transfer marine technology, particularly to benefit small island developing States and least developed countries

[14] https://www.earthobservations.org/documents/GEO_Strategic_Plan_2016_2025_Implementing_GEOSS.pdf
[15] https://www.earthobservations.org/documents/GEO_Strategic_Plan_2016_2025_Implementing_GEOSS.pdf
[16] https://sustainabledevelopment.un.org/sdg14

Present observation activities are key to meeting the need to monitor fishing activity (including of trans-boundary tuna stocks) and nutrient loading in coastal regions, and are being upgraded to deal with new scientific understanding of existing pressures and new forms of pollution. The Global Ocean Acidification Observing Network[17], for example, is being built up to monitor changes in ocean pH resulting from climate change. Plastics, and micro-plastics in particular, are a more recent concern; groups such as Blue Planet[18] (the oceanic component of the Group on Earth Observations) are working on technologies to track and model plastics in the ocean.

Biological Diversity

The *Convention on Biological Diversity* (CBD) has three main goals: conservation of biological diversity; sustainable use of its components; and fair and equitable sharing of benefits arising from genetic resources. As part of the United Nations Decade of Biodiversity (2011-2020), the Aichi Biodiversity Targets[19] were developed, comprising 20 targets for the year 2020 within five strategic goals. These goals, along with some of the targets relevant to ocean observing are:

1) Address the underlying causes of biodiversity loss
    - subsidies and other incentives harmful to biodiversity are eliminated and positive incentives to conserve and sustainably use biodiversity are in place
    - governments, business and other stakeholders have implemented plans for sustainable production and consumption so impacts are well within safe ecological limits
2) Reduce the direct pressures on biodiversity and promote sustainable use
    - the rate of loss of all natural habitats is greatly reduced or eliminated
    - fish and invertebrate stocks and aquatic plants are managed and harvested sustainably, under ecosystem-based management, with recovery plans in place for depleted species
    - aquaculture is managed sustainably
    - pollution, including from excess nutrients, has been reduced to levels not detrimental to ecosystem function and biodiversity
    - invasive alien species are controlled or eradicated and introduction pathways are managed
    - pressures on coral reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification are minimised
3) Improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity
    - at least 10% of coastal and marine areas conserved in protected areas
    - genetic diversity of cultivated and wild organisms is maintained, and genetic erosion is minimised
4) Enhance the benefits to all from biodiversity and ecosystem services
    - ecosystems that provide essential services are restored and safeguarded
    - the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization are in force
5) Enhance implementation through planning, knowledge management and capacity building
    - each signatory has developed and implemented a national biodiversity strategy
    - knowledge, the science base and technologies relating to biodiversity, its values, functioning, status and trends, and the consequences of its loss, are improved, widely shared and transferred, and applied

Each of these targets require increased scientific understanding of biodiversity – its current status, trends, and pressures and drivers – to establish policies, incentives, and regulations, as well as monitoring, to

[17] http://goa-on.org/home.php
[18] http://www.gstss.org/2018_Brest/
[19] https://www.cbd.int/sp/targets/

properly manage protected areas and enforce fishing, transport, and other industrial activities. The ocean data needed to support the CBD includes physical, biogeochemical, as well as biological data, including genetic information which is being advanced within ‘omics networks (see Section 3.1.6).

<u>Other Accords</u>

The United Nations Framework Convention on Climate Change (UNFCCC's) Paris Agreement adopted by COP-21 in December 2015 sets out an ambitious climate agenda with a formal limit to the increase in the global average temperature to “well below 2 °C”, noting the importance of "ensuring the integrity of all ecosystems, including oceans", and recognizing the importance of "systematic observation" in the context of climate change adaptation, and insisting that actions must be taken in accordance with the "best available science."

The *Sendai Framework for Disaster Risk Reduction*[20], launched in response to an earthquake and tsunami which killed 18,000 people and resulted in a nuclear meltdown in 2011, provides a new global approach to disaster risk management policy and operations, focusing on understanding disaster risk, strengthening governance, and investing in risk reduction and preparedness.

Other agreements of relevance to oceans include those from the International Seabed Authority, the International Maritime Organization (e.g., pollution), the United Nations Environment Programme’s Global Program for Protection of the Marine Environment from Land-Based Activities, and the Food and Agriculture Organization (FAO).

The GOOS Biology and Ecosystems Panel analysed 24 global and regional agreements or international bodies that identify the need for sustained monitoring of ocean ecosystems or biological variables, in order to extract the key Drivers for observations and the Pressures identified of human impact on marine biodiversity and ecosystem health[21] (Table 2). Their concept is to use a Drivers-Pressures-State-Impact-Response (DPSIR) framework to identify the requirements for sustained monitoring of biological and ecosystems Essential Ocean Variables. They found that the major drivers for observations across these agreements and the major pressures on ocean ecosystems are (in decreasing order):

Pressures
loss of resources, habitat, biodiversity
climate change
pollution and eutrophication
coastal development
invasive species
solid waste
ocean acidification
extreme weather events
noise
mining

Drivers
knowledge to better understand pressures
sustainable use of biodiversity and living resources
conservation of biodiversity and ecosystems
improving management through ecosystem approaches
sustainable economic growth and development
capacity building
threat prevention and impact mitigation
environmental quality and protecting health
food security

Table 2: Pressures and Drivers from International and Regional Accords[22]

[20] https://sustainabledevelopment.un.org/frameworks/sendaiframework
[21] https://hal.archives-ouvertes.fr/hal-01826619/
[22] https://hal.archives-ouvertes.fr/hal-01826619/

2.1.4 Regional Drivers

Europe has systems, agreements, and laws related to a number of high-level benefit areas that require ocean information. In **climate**, the Copernicus Climate Change Service (C3S) has a mission to “support adaptation and mitigation policies of the European Union by providing consistent and authoritative information about climate change”[23] and offers free and open access to climate data and tools, as well as training to users including scientists, policy-makers, the media, and the public. For its observational (in-situ and satellite) component, the C3S relies on multiple Essential Climate Variables used to generate global and regional re-analyses (covering a comprehensive Earth-system domain: atmosphere, ocean, land, carbon). For the ocean, ECVs are similar to EOVs, but with the associated uncertainty information needed to qualify these observations to be climate relevant. C3S is one of six thematic information services provided by the Copernicus Earth Observation Programme of the European Union, along with marine monitoring. It is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission as an independent intergovernmental organisation. C3S relies on climate research carried out within the World Climate Research Programme (WCRP), responds to user requirements defined by the Global Climate Observing System (GCOS), and provides an important resource to the Global Framework for Climate Services (GFCS).

The Copernicus Marine Environmental Monitoring Service (CMEMS), which became operational in May 2015, provides **operational services**, including daily analyses and forecasts, as well as products such as Ocean State Reports, web-based ocean monitoring indicators[24] to track the state and health of the ocean, and reanalyses. The Marine Strategy Framework Directive notes that ocean information is needed to improve knowledge of the seas and oceans, one of the three cross-cutting tools of the EU’s Integrated Maritime Policy. In-situ marine observations, satellite data, and operational numerical model products shape the core services for users in four social benefit areas: **maritime safety** (e.g., ship route optimisation; oil spill response), **marine resources** for the protection and sustainable use of living marine resources (e.g., sustainable aquaculture; fisheries), **coastal and marine environment** (e.g., tsunami warning; coastal erosion), and **weather, seasonal forecasting and climate** (e.g., boundary conditions for weather forecast models). In June 2016, the European Commission published an action plan to translate the Sendai priorities into EU policies, noting that marine environment monitoring is a key component of the Copernicus Emergency Management Service to support “crisis managers, civil protection authorities and humanitarian aid actors dealing with natural disasters, man-made emergency situations and humanitarian crises, as well as those involved in preparedness and recovery activities.”[25]

In **ocean health**, the Marine Strategy Framework Directive (MSFD), the environmental component of Europe's Integrated Maritime Policy, is designed to protect the marine environment across Europe. It creates a framework for sustainable use of Europe's marine waters, mandates an ecosystem approach to management, and sets a target of "Good Environmental Status" which must be achieved in EU marine waters by 2020. Each Member State must pass targets in 11 areas, including biodiversity, safeguarding commercial species, eutrophication, contaminants, marine litter, and energy and noise. There are other regional organisations concerned with ocean health in European oceans as well. For example, Regional Fisheries Management Organisations (RFMOs) are international organisations dedicated to the sustainable management of fishery resources in a particular region of international waters, or of highly migratory species; while some have a purely advisory role, most have management powers to set catch and fishing effort limits, technical measures, and control obligations. The Northwest Atlantic Fisheries Organization (NAFO) and the International Commission for the Conservation of Atlantic Tunas are two RFMOs relevant to the northwest Atlantic. The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) regulates cooperation on the protection of the marine environment in the North-East Atlantic and includes

[23] https://climate.copernicus.eu/about-us
[24] http://marine.copernicus.eu/science-learning/ocean-monitoring-indicators/catalogue/
[25] http://ec.europa.eu/echo/files/aid/countries/factsheets/thematic/sendai_en.pdf

annexes on dumping at sea, land-based sources, biodiversity and ecosystems, and impacts from non-polluting human activities. It is guided by an ecosystem approach to the integrated management of human activities and requires that Member States apply the precautionary and polluter-pays principles. OSPAR's Intermediate Assessment 2017[26] updates progress on areas of concern studied in the latest Quality Status Report from 2010, including how benthic habitats are affected by bottom fisheries, new developments in how biodiversity is assessed, and the status of marine birds, marine litter, and discharge from oil and gas installations.

2.2 Applications and Phenomena

The ultimate goal of the ocean information value chain is the provision of timely, relevant, effective, and efficient high-level societal benefits. These outputs require, as inputs, raw data, analysis, modelling, scientific expertise, and communication in formats useful to the end user. The Framework for Ocean Observing outlines how to bridge the link between user-driven social benefits and the ocean observations (Section 3.1) and analyses needed to address them: applications, scientific questions, and phenomena.

Applications are the deliverable information (e.g., weather report or risk assessment) needed to create a societal benefit. Applications are the visible end-product of the ocean information value chain, its communication to the public, and its demonstration of value for investing in ocean observing, analysis, and modelling activities. In Work Package 8 (Societal benefits from observing/information systems), the AtlantOS project delivered a series of pilot products targeted at issues of societal concern in European Member States, including warnings for Harmful Algal Blooms, ship routing hazard mapping, offshore aquaculture siting, and operational real-time and forecast modelling of North Atlantic tuna populations. The idea was not to develop commercial products but to showcase possible uses of ocean information, and, in a series of reports available on the AtlantOS website[27], determine the adequacy of the ocean information value chain in supporting these applications. Constant dialogue between end users, application developers, and ocean observers and modellers to develop and enhance ocean applications will benefit information providers, by raising the profile and value of the ocean information value chain, as well as the end users.

Applications, by their nature, encompass a range of inputs and considerations. The move to ecosystem-based management is only one example of a more recent demand to understand issues in a more holistic and integrated manner. Risk assessments are increasingly concerned with the cumulative effects of varied pressures such as the interactions between chemicals in the environment. Marine Spatial Planning is growing in importance as the ocean landscape becomes more crowded with increased conventional (e.g., shipping) and new (e.g., ocean energy and biotechnology) industries.

This multi-factored approach to ocean management requires integrated data and integrated understanding of scientific processes. While scientists can no longer examine the effects on fish stocks, for example, from individual pressures separately, the entire system is too complex, and present knowledge not sufficiently advanced, to consider the ocean environment as a whole – scientists must consider components of the systems that are affected by common processes. There are multiple approaches in how to think about these subsystems, which arise, in part, due to the different nature and histories of the users of ocean information, of the different scientific sub-disciplines studying the ocean, and the diversity of those in industry, science, and government running observation programs.

The physical, biogeochemistry, and biology/ecosystem panels of GOOS meet regularly to further integrate ocean knowledge, approaches, and observation activities across their disciplines, including to develop a

[26] https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/
[27] https://www.atlantos-h2020.eu/project-information/work-packages/deliverables/

common language, to optimise the ocean information value chain. At its 2016 Cross-Panel meeting[28], GOOS defined a phenomenon as "an observable process, event, or property, measured or derived from one or a combination of EOVs, having characteristic spatial and time scale(s), that addresses at least one GOOS Scientific Question" and also agreed upon a harmonised list of 27 phenomena to better understand the ocean and its role in the larger Earth-system and in human society, as well as the needs of specific users of ocean information:

- circulation
- ventilation
- fronts and eddies
- tides
- upwelling
- coastal processes
- stratification and mixed layer
- surface waves
- near inertial oscillations
- sea level
- sea ice extent
- extreme events
- air-sea fluxes
- land-ocean fluxes
- benthic fluxes
- ocean acidification
- deoxygenation
- eutrophication
- contamination / pollution
- storage (i.e., of heat, freshwater, and carbon in the ocean and its biota)
- anthropogenic carbon sequestration
- remineralisation
- export fluxes
- production / calcification (e.g., primary production & the quality / extent of marine habitat)
- change / community shifts (e.g., regime shift, species composition, species range)
- impact of changes (e.g., population loss, mass mortality, bleaching)
- resilience / recovery (e.g., recruitment, restoration, hysteresis)

These phenomena, which are the intellectual integrations of interactions in the natural system that need to be scientifically understood (and thus the link between observations and applications) will continue to evolve and be refined as high-level user needs are refined and better understood through feedback from users on the associated applications. The space and time scales as well as the variables that help describe a phenomenon are important to identify in order to develop traceability in requirements placed on the observing system. This traceability to specific applications and phenomena is important when setting priorities; the fitness of the ocean observing system is better measured using phenomenon-based metrics rather than those based on Essential Ocean Variables or on observing platforms, but these metrics have yet to be established (see Section 3.4).

[28] file:///C:/Users/m_ott/Downloads/GOOS_cross-panel_Sep_2016_Decisions_Actions_vfinal%20(4).pdf

2.3 Essential Ocean Variables

Essential Ocean Variables (EOVs) are the Framework for Ocean Observing concept of the fundamental physical, biogeochemical, and biological measurements needed for the scientific understanding of ocean phenomena and the provision of applications in support of Societal Benefits. Their essential nature denotes that these observables are the minimum subset required to meet the needs for ocean information and cannot be replaced by other variables. While there are a large number of observations that can be made, feasibility and impact are both important in determining whether a variable is essential. According to the Framework for Ocean Observing[29], high feasibility implies that the observations can be made at the time and spatial scales, and with the accuracy and cost-effectiveness, necessary to capture the required phenomena and high impact implies that the variables being measured drive understanding, and are needed for applications and societal benefits.

EOVs, then, are the basic variables that need to be measured, and thus the foundational input into the applications serving to address societal benefits; each application requires a (different) combination of EOVs. With different scientific and political interests, funding regimes, technical requirements, and capacity, it is not surprising that the observing community is comprised of projects and activities exhibiting a wide variety of sensors, platforms, and models of governance, best practices, and data management. While this free-market approach to observing projects has its advantages (in faster response to local needs and in technological innovation, for example), the drawbacks include isolated silos of activity, leading to increased costs, inaccessible data, and poorer applications.

At the level of ocean observations, the aim of the ocean information value chain is to measure the ocean variables in the most effective and cost-efficient manner possible, which includes the need for shared platforms and best practices to reduce cost and enable data sharing and re-use ("measure once, use many times"). The first step, an agreement on a common set of variables, has led to the list of EOVs approved by GOOS[30] (Table 3).

• sea state	• particulate matter
• ocean surface stress	• nitrous oxide
• sea ice	• stable carbon isotopes
• sea surface height (SSH)	• dissolved organic carbon
• sea surface temperature (SST)	• phytoplankton biomass and diversity
• subsurface temperature	• zooplankton biomass and diversity
• sea surface salinity (SSS)	• fish abundance and distribution
• subsurface salinity	• marine turtles, birds, mammals abundance and distribution
• surface currents	• hard coral cover and composition
• subsurface currents	• seagrass cover and composition
• ocean surface heat flux	• macroalgal canopy cover and composition
• oxygen	• mangrove cover and composition
• nutrients	• microbe biomass and diversity
• inorganic carbon	• invertebrate abundance and distribution
• transient tracers	• ocean colour
	• ocean sound

Table 3: GOOS Essential Ocean Variables[31]

[29] http://www.oceanobs09.net/foo/FOO_Report.pdf
[30] http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114
[31] http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114

Re-using data for multiple purposes requires more than a common set of EOVs, however; observation protocols (e.g., time and spatial resolution, and uncertainty) must be compatible and meet the needs for each end-user and application, and thus be carefully considered by the proponents of each observing project. The ocean community has considered the observation requirements for each EOV in relation to their associated phenomena, and have produced EOV Specification Sheets (available on the GOOS website[32]) describing the EOVs: their importance in and links to scientific phenomena, present observation strategies (e.g., spatial and temporal resolution, accuracy, technological readiness level), required complementary variables, derived variables, and the observation programmes and networks measuring the data.

Individual EOVs are at differing stages of maturity, with physical EOVs being the most firmly established. However, descriptions of even the most mature EOVs evolve with new observation technologies, measurement techniques and algorithms, with improved understanding of the links between different EOVs (i.e., complementarity) and between EOVs and scientific phenomena, and with better knowledge of the user's needs and resulting applications. As a result, the EOV Specification Sheets are continuously being refined. They describe in detail, for example, how each EOV is related to ocean phenomena; short descriptions are provided here.

Sea State impacts marine safety, marine transport, and may damage marine structures; waves, generated by ocean surface vector stress and modified by bathymetry and surface currents, affect air-sea exchanges of momentum, freshwater, and CO_2, and also impact beach erosion, storm-related water damage, the transport of larva and contaminants such as oil, and the growth and decay of sea ice.

Ocean Surface Stress, the rate at which horizontal momentum is transferred from the atmosphere to the ocean, influences the air-sea exchange of energy (sensible and latent heat), water (evaporation) and carbon dioxide (CO_2). It is critically important for determining large-scale ocean currents and transport, (coastal and open ocean) upwelling and downwelling (including mixed layer evolution and deepwater formation), primary productivity, and cross shelf transport (of, for example, fish larvae and pollution).

Both the presence or absence of **Sea Ice** (albedo and evaporation) and changes in sea ice (latent heat) heavily impact local and global energy balances. Sea ice also alters currents, affecting stress and driving strong vertical transport near the ice edge, and melting and freezing strongly alters the local salinity, impacting stratification and local currents. Primary parameters for sea ice are: concentration / extent / area, motion, seasonality, age and thickness, as is the thickness of the insulating snow cover which impacts melting and freezing rates.

Sea Surface Height (SSH), or sea level, has been identified as one of the primary indicator of global climate change; global mean sea level change provides a measure of the net change in ocean mass due to melting of glaciers and ice sheets and the net change in ocean volume due to thermal expansion. At the coast, atmospheric forcing can cause significant departures of SSH from the harmonic tide, leading to inundation or issues for navigation due to lower water levels.

Sea Surface Temperature (SST) exerts a major influence on the exchanges of energy, momentum and gases between the ocean and atmosphere, and heat exchanges are a main driver of global weather systems, including extreme events like hurricanes. Real-time data, from polar-orbiting and geosynchronous satellites, is crucial for forecasting. Climate applications require very stringent accuracies of 0.1K and stabilities of 0.03K/decade.

Changes in **Subsurface Temperature** impact many ocean services, including the growth rate of farmed fish as well as the distribution and abundance of wild fish stocks and other marine species of significant economic and social value. Changes in subsurface temperature also affect mixed-layer depth, vertical and lateral ocean

[32] http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114

thermal / density stratification, mixing rates, and currents, which then impact marine biology directly and indirectly through changes in marine biogeochemistry, such as nutrient and oxygen recycling, uptake of (anthropogenic) carbon emissions, and ocean acidification. Subsurface observations also validate satellite-derived SST data, and are critical in many weather and climate applications, including forecasting and understanding the ocean heat content, the global energy budget, and sea level change.

Sea Surface Salinity (SSS) is a key parameter for monitoring the global water cycle (evaporation, precipitation, and glacier and river runoff) and observations over large scales can be used to infer long-term changes in the hydrological cycle and to quantify the evolution of the ocean in response to climate change. SSS is a key component in determining the evolution of the surface expression of fine to large-scale ocean frontal features and eddies, which strongly impact the diversity and health of the ocean ecosystem.

A global **Subsurface Salinity** observing system is vital to close the global hydrological cycle and understand the halosteric component of sea level change. Subsurface salinity is key to calculate density and also freshwater transport. As for temperature, i) changes in salinity affect mixed-layer depth, vertical and lateral ocean thermal / density stratification, mixing rates, and currents, and thus marine biology; and ii) salinity observations validate satellite-derived SST data, and are critical in many weather and climate applications.

Surface Currents transport significant amounts of heat, salt, passive tracers, and ocean pollutants. At the basin-scale, zonal surface currents and their variations are key in climate to weather fluctuations. Convergences/divergences, spiralling eddies, and filaments all contribute to vertical motion and mass exchange, including upwelling, which leads to productive fisheries. Surface currents impact the steepness of surface waves, important for accurate marine sea state forecasts. By advecting passive particles, surface current data are also key to applications such as oil spill and marine debris response, search and rescue , and ship routing. Currents, particularly tidal currents, can also modify storm surge impacts and sea level changes.

Observations of **Subsurface Currents** are needed to estimate oceanic transport of mass, heat, and freshwater, and are particularly important in resolving the complex velocity structure of the major boundary currents, at the sea floor, near the equator, in ocean eddies, and in waves. Velocity profile information is also used to roughly estimate ocean mixing using fine-scale parameterizations of turbulent dissipation by internal wave-breaking, which affects the global ocean energy balance as well as primary production.

Ocean Surface Heat Flux due to evaporation (latent heat) and differences in air-sea temperatures (sensible heat) is a major contributor to the energy budget, and the main thermodynamic coupling of the ocean and atmosphere at global and regional scales. Variations in these fluxes leads to large-scale variability in weather and climate patterns; they are sensitive indicators of changes in climate, including floods and droughts, and storm tracks and intensity.

Sub-surface **Oxygen** concentration is a balance among circulation, ventilation, production (photosynthesis), and consumption (respiratory and decomposition processes). The amount of oxygen dissolved in the ocean has decreased significantly in most parts of the ocean over the past few decades, partly due to warmer ocean temperatures (which also increases the oxygen demand from organisms), impacting the ecosystem and food chain, including krill, a key part of the diets of fish, squid, and whales. Some species (e.g., jellyfish are tolerant of lower oxygen levels, but many are not, as evidenced by large fish and crustacean die-offs which occur during low-oxygen events. Even where mortality is not affected, growth and reproduction are impacted.

The availability of **Nutrients** in the upper ocean frequently limits and regulates primary productivity, and eventually fish stocks, as well as the amount of organic carbon fixed by phytoplankton, thereby constituting a key control mechanism of carbon and biogeochemical cycling. There are a number of biogeographic regions in the open ocean Atlantic characterised by different macronutrient regimes, which permanently or seasonally limit the growth of phytoplankton. Measuring changes in macronutrient concentrations is essential to constraining net biological production and export fluxes, detecting shifts in biogeographic regimes, but also monitoring eutrophication and pollution phenomena.

Inorganic Carbon – The ocean is a major component of the global carbon cycle, exchanging massive quantities of carbon with the atmosphere and biosphere in natural cycles driven by the ocean circulation and biogeochemistry. The ocean has absorbed 25% of anthropogenic carbon emissions, significantly reducing the accumulation in the atmosphere and the rate of global warming. However, this uptake is causing ocean acidification (a decrease in pH), which limits the ability of shellfish to build protective shells and corals to build their internal skeletons, as well as impacting their reproductive capability. Studies have also shown that ocean acidification affects the behaviour of fish directly, including impairing their sense of smell.[33]

Transient tracers are chemical compounds that are either conservative (i.e., no sources or sinks, such as chlorofluorocarbons) in seawater or have well-defined decay-functions (e.g., radioactive isotopes such as tritium), and a well-known source at the ocean surface. They are used to follow water masses in the ocean and track the time since the water has been in contact with the surface, which is useful to quantify ventilation strength, transit time distribution, and transport time-scales. Knowledge of the transit time distribution of a water-mass allows for inference of the concentrations or fates of other transient compounds, such as anthropogenic carbon or nitrous oxide.

Suspended **Particulate Matter** includes the variables Particulate Organic Matter (POM, i.e. Particulate Organic Carbon (POC) and Particulate Organic Nitrogen (PON)), but also particulate inorganic carbon (PIC) and biogenic silica (BSi), as well as the vertical transport (export) flux of all particulates. Changes in POM indicate deteriorating water quality due to eutrophication in coastal regions, and of declines in primary production that could potentially translate up the food chain, negatively impacting biomass, including fisheries. Observation of PIC address the question of what impacts ocean acidification has on calcareous organisms and thus community structure.

The oceans are a major source for **Nitrous Oxide** (N_2O), an important climate-relevant trace gas, accounting for about 30% of the atmospheric budget. While chlorofluorocarbons continue to decline, N_2O is increasingly becoming more important to both the greenhouse effect and ozone depletion. Monitoring helps us not only understand climate change, but also captures information about such ocean phenomena as deoxygenation, eutrophication, and upwelling.

Recent improvements in measuring the **Stable Carbon Isotopes** (the carbon-13 to carbon-12 isotope ratio 13C/12C) are enabling substantially improved δ13C-based estimates of organic matter export rate and of the air-sea $13CO_2$ flux, which allow for the tracking of sources of anthropogenic carbon. Recent application of this approach in the North Atlantic, for example, indicates that 50% of the anthropogenic CO2 increase in this ocean basin is a result of transport from the South Atlantic as part of the Meridional Overturning Circulation.

In the ocean, the inventory of **Dissolved Organic Carbon** (DOC) is 200 times that of organic particles; DOC is the second largest bio-reactive pool of carbon in the ocean (after dissolved inorganic carbon). The size of the reservoir (similar to that of atmospheric carbon dioxide), as well as its role as a sink for autotrophically-fixed carbon, as a substrate to heterotrophic microbes, and as a sink/source of carbon involved in climate variations over long time scales, highlights its importance in the ocean carbon and nitrogen cycles.

Phytoplankton Biomass and Diversity is the base of the food web, accounting for 50% of oxygen produced on the Earth. Changes can affect fishery catch potential, patterns of Harmful Algal Blooms (HABs, which can also affect human health), the dispersal of invasive or introduced species, and cause other shifts in marine habitats of the coastal zone, the continental shelf, or the open ocean, many that we have yet to recognise.

[33] https://www.cencoos.org/learn/oa/impacts

Phytoplankton biomass and diversity are also affected by pollution (including nutrient runoff) and grazing pressures from higher trophic levels (e.g., zooplankton and fish). Multiple observing tools are needed to characterise the biological diversity of these organisms, their phenology, vertical distribution, and community composition (species and genomics), and their role in ocean biogeochemistry and ecosystem services.

Zooplankton Biomass and Diversity – zooplankton are an intermediary between primary productivity and higher trophic levels and also play a key role in ocean chemistry by recycling nutrients and carbon in near-surface waters of the ocean and by delivering these materials to deeper ocean waters through defecation and through daily and ontogenetic migration. Zooplankton biomass is an important and commonly used variable to evaluate fisheries potential and ecosystem health, while diversity influences ecosystem health and productivity through trophic links and is affected by environmental pressures such as climate change, including ocean acidification, warming, and deoxygenation.

Fisheries provide food for a large fraction of the world's population, meal and oil for aquaculture, and livelihoods for fishers. Fish and fisheries occupy important roles in societies, including traditional cultures. Measurements of **Fish Abundance and Distribution** are useful to inform a variety of types of decisions, including those that involve fisheries management, conservation and sustainable use policies, and those that affect economic investment and societal resilience in the face of climate change. The biomass or numbers of fish can be measured by species, or by taxonomic or functional groups, and reported at local, national, regional, or global scales.

Wide-ranging, relatively long-lived and large-bodied species play a crucial role in maintaining the health of their ecosystems, influence population dynamics and distribution of numerous prey species, and integrate biological factors, such as toxins, in their bodies. Measurements of **Marine Turtle, Bird, and Mammal Abundance and Distribution** allow us to evaluate these interactions and their variability. These species are particularly vulnerable to human impacts such as fisheries (e.g., bycatch and reduction of prey species) and climate change (e.g., reduction of habitat), provide longer-term indicators of ecosystem health, and can act as a sentinel for human health risks.

Monitoring **Hard Coral Cover and Composition** is critical to protecting coral reefs, among the most biodiverse and highly-valued ecosystems for their ecosystem goods and services, and also one of the most threatened. Healthy coral reefs are a foundation for the livelihood and food security of many people in low-income tropical countries and provide products for global markets, including ornamental fish, cement, and tourism and recreation. Climate change, ocean acidification, fisheries, pollution, and development are all significant threats to coral reefs, which are particularly vulnerable because they are slow-growing and susceptible to stress, particularly when there are synergies between natural and anthropogenic stresses.

Seagrass Cover and Composition are deteriorating due to coastal development, nutrient loading that leads to poor light conditions on the seafloor, climate change, and cascading impacts of fishing. Seagrasses can form dense, submerged meadows in coastal and estuarine waters, are often highly productive, provide essential habitat and nursery areas for many finfish, shellfish, charismatic megafauna (including sea turtles), help stabilise and protect coasts by binding underlying sediments, reduce the acidity of surrounding water by removing dissolved carbon dioxide through photosynthesis, and contribute to good water quality by trapping sediment and absorbing nutrient runoff. They are also a "blue" carbon storage system - fixing inorganic carbon via photosynthesis and storing it in seagrass rhizomes and associated sediments; comprising only 0.2% of the world ocean they contribute >10% of all carbon buried annually in the sea.

Macroalgal forests (dominated by kelp and fucoid brown algae) are highly diverse ecosystems that provide many important functions and services, including high primary production, provision of nursery areas, food resources, and protection from coastal erosion. Monitoring **Macroalgal Canopy Cover and Composition** is key to protecting these ecosystems from ocean warming and regional stressors resulting from intensifying human activities along the coast, including habitat degradation, pollution, eutrophication, and the spread of invasive species. Macroalgal forests provide a sensitive and well-understood indicator of changing coastal marine environments, potentially allowing the early detection of impending regime shifts. Furthermore, their broad distribution from boreal to temperate regions allows for comparison of latitudinal trends and the tracking of geographic shifts in species ranges.

Although mangroves mediate key biogeochemical fluxes, are highly productive, and support rich diversity, they are severely threatened, with about 1% destroyed each year globally due to unsustainable forestry, agriculture and aquaculture, urbanisation, and rising sea level. Monitoring **Mangrove Cover and Composition** allow us to protect these ecosystems and the services they provide: protecting coastal communities from erosion and damage from storm surges, filtering terrestrial run-off, supplying timber, and generating significant revenue through ecotourism and biodiversity conservation. Mangroves provide critical nursery, with each hectare of fringe mangrove in the Gulf of California, for example, estimated to provide $37,500 (U.S.) per year in fisheries production. Globally, mangroves sequester and store more carbon than almost any other type of ecosystem.

Microbe Biomass and Diversity is an emerging EOV; we are learning more about the role of microbes (impact), including in altered ecosystems, and technologies are becoming more available and affordable (feasibility). Ocean microbiome research has pointed towards their use as indicators of ecosystem stress and their role in biogeochemical processes in the ocean and as primary producers; as meta-omics technologies are further refined, monitoring microbes will become increasingly important in understanding environmental effects on biodiversity.[34]

Invertebrate Abundance and Distribution is another emerging EOV. Marine invertebrates, such as crabs, jellies, seastars, sponges, shrimp, and octopuses, account for over 50% of the marine species in Europe's oceans, coastal waters, and estuaries. They fill many important roles and are responsible for delivering a wide range of ecosystem services. However, present knowledge of the health of marine invertebrates at large scales is very limited. "In 2012, EU Member States collectively provided 30 assessments of marine invertebrates under the MSFD. All 30 assessments were categorised as being 'unknown' with respect to environmental status … while 25% of species assessed in the Northeast Atlantic Ocean were in unfavourable conservation status.[35]"

Ocean Colour is the spectral radiance emanating from the sun that is backscattered off the upper part of the oceanic water column. It contains information on the biological, biogeochemical, and ecological properties of water and its constituents; changes in ocean colour can be related to changes in the presence and magnitude of living and non-living particles and of dissolved materials in the water, including phytoplankton and silt. Ocean colour can be used to differentiate and classify different water bodies because the colour of any particular ocean region depends on the proportion, type, and vertical distribution of different dissolved or particulate materials and the depth of the water. Ocean colour is useful for evaluating the health of an ecosystem and to inform resource management, such as fisheries and recreation, in the coastal and open ocean but also in lakes and other inland water bodies. It is also useful to estimate water quality and the amount of heat that accumulates as the ocean absorbs sunlight.

Ocean Sound is among the most effective ways to probe the marine environment and communicate over long distances because sound propagates very well in the ocean. Many marine animals produce sound (e.g., shrimp and whales) and acoustic cues are critical for animals (e.g., for larvae to settle in appropriate environments). Humans use sound to detect objects (e.g., fish schools), to map the seafloor and to measure sea ice thickness. Systems to use sound to monitor the status of populations, habitats, and ecosystems are being developed to replace visual sightings. Sound is already used to measure the average temperature of the ocean over long distances. Research is also being conducted into how anthropogenic sources of sound, such as marine traffic, affect marine life.

[34] https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.14108

[35] https://water.europa.eu/marine/topics/state-of-marine-ecosystem/marine-invertebrates

3 Response to High-Level Requirements

Translating high-level user needs into requirements for observations necessitate, as a first step, that scientists and observation programs understand which ocean parameters (EOVs) are needed to create and enhance the applications and tools which can inform management, policy-making, and enforcement decisions. In addition, the specific sampling requirements (e.g., temporal and spatial resolution, as well as accuracy) for each variable must be clearly defined, and these can differ for the same EOV in different applications. These requirements can also vary greatly with location (e.g., coastal, boundary current, or deep ocean compared to open ocean).

Obtaining such a clear picture is very difficult in an environment with shifting political priorities, funding constraints, and rapidly developing technologies, and calls for continuous dialogue between users and observers. Once these requirements are properly known, a capacity and gap analysis can be performed to determine whether the present observing system can supply the relevant ocean data. There are any number of reasons why this might not be the case – AtlantOS has identified several types of gaps:

- observational – uneven geographical coverage; major gaps in the collection of biogeochemical and biological / ecosystem data; lack of data in the deep ocean
- data availability – institutions that have strict data policies (e.g., the military), that sell data, or that do not properly manage and archive data
- technology – new instruments needed (e.g., higher quality, or new variables, such as 'omics) to meet emerging needs
- sustainability – lack of funding (70% of ocean observation programs exist on time-limited research funds)

The AtlantOS project has, with partners including GOOS and the GEO Blue Planet Initiative, worked over the past several years to further integrate existing and more recent ocean observing programs into a more comprehensive and fit-for-purpose Atlantic Ocean observing system, utilizing the Framework for Ocean Observation; ensuring a focus on Essential Ocean Variables; encouraging the collection of compatible metadata; enhancing links between the biological and coastal observation communities; prioritizing free and open access to data; supporting sensor development; and standardizing language and best practices.

AtlantOS has examined user needs, including through pilot project in WP8 (Societal benefits from observing/information systems) and in national surveys piloted in WP9 (System evaluation and sustainability), developed a technology roadmap for near-future ocean observation technologies, produced a cost and feasibility study of present and future ocean observing, and run a series of Observing System Evaluation (OSE) and Observing System Simulation Experiments (OSSE) trials and developed new ocean simulation techniques to begin to quantify the importance of different ocean observation data types in reducing model error and uncertainty, and improving forecasts.

At a Future Ocean Observing Design Workshop, AtlantOS synthesised these results, along with individual networks' future plans and strategic goals, to envision a future fit-for-purpose integrated ocean observing system for the Atlantic Ocean. In the following sections, the response of networks and numerical modelling to user needs are described, and a number of recommendations are put forth to improve the entire ocean information value chain to meet the needs of society, industry, and the environment.

3.1 Networks

Individual observing networks operate at widely different maturity levels – some (e.g., Argo), are well-established internationally-coordinated programs based on concrete plans addressing well-posed scientific or societal questions, while others (e.g., genomics) are just starting and are based on new or developing technologies. They have developed in different historical contexts – some (e.g., drifters) focused on global targets, while others are an upscaling or integration of local and regional developments. There is a range from diversity (e.g., ETN is very flexible) to standardisation (e.g., Argo has strict rules) in implementing new measurements, each with advantages and disadvantages. Some networks transmit data in real-time, others in delayed model. Networks have different levels of maturity with respect to data management, data usage (operational vs. only scientific interest at the present), and sustainability (e.g., Argo's core mission is fully sustained, while gliders are looking for funding). These differences make integrating network plans, and sharing platforms, more challenging.

In general, due to ease of measurement / understanding and sensor technology readiness levels, physical observations have appeared first (including on newly developed autonomous platforms), followed later by biochemical and biology / ecosystem measurements. While there are platforms and networks that have multi-disciplinary objectives (e.g., OceanSites), there are still platforms with only physical (e.g., Transport Mooring Arrays, drifters) or biological (e.g., European Tracking Network) observations. While cooperation between networks exists, links between open-ocean and coastal observation systems need to be considerably strengthened, as do links to the newly emerging biological networks.

Overall, there is a need to fill gaps in the observation network by measuring more (increasing the diversity of parameters, particularly for biology, but also in geographically-neglected areas such as boundary currents and the deep ocean) and better (e.g., increased temporal and spatial resolution). This requires new sensors, platforms, and funding models, and improved data streams (e.g., standardisation, interoperability, and real-time quality control), and changing the culture in the observation community from research-driven to interactive and community-based (e.g., deeper coordination with MBON, the Marine Biodiversity Network).

AltantOS Work Package 2 (Enhancement of ship-based observing networks) identified several barriers to integration: cost of research cruises; lack of funding outside national EEZs; data volume; national restrictions on the data; and (specifically for ships of opportunity) rapid changes in the shipping industry. In addition, there is general agreement that coverage in the South Atlantic needs to be improved. Recommendations to facilitate integration include: redesigned instrumentation to make it much more portable; improved sharing of acoustic raw data for fish, zooplankton, and bathymetry; and a dedicated European team to coordinate research cruises.

Work Package 3 (Enhancement of autonomous observing networks) also identified a number of barriers to integration: difficulties in planning and projecting the future of an integrated observation system while the sustainability of many core missions is not yet secure; the monopolistic environment of a few sensor companies setting prices, causing delays, and potentially stifling innovation and quality of measurements; and the (declining) resistance to deliver and share data. Recommendations to foster integration include: continued fostering of technology development of EU sensors and platforms; the need to educate network operators (and not just information users) of the future; strengthening cooperation between network operators and network designers; ensuring funders demand future observation programmes include components to quality control, archive, and make available data; and continue to develop infrastructures (e.g., ERICs) and mechanisms (e.g., JCOMMOPS) to facilitate network integration.

Deliverable 6.6[36] ("The Shared Infrastructure Report") outlined initiatives and technological innovations supporting integration, and several constraints and local requirements making integration more difficult. In preparation for the report, AtlantOS Task 6.3 (Shared infrastructure) held several workshops among network operators, among network infrastructure providers (e.g., ERICs), and at a more strategic level (i.e., AORA[37], the Atlantic Ocean Research Alliance). The report looked at several areas of infrastructure sharing, including vessels (ship-time) and receivers for animal tracking, and addressed legal considerations, but its conclusions

[36] https://www.atlantos-h2020.eu/download/deliverables/D6.6_Integrated%20Atlantic%20Ocean%20Observing%20System_final.pdf
[37] https://www.atlanticresource.org/aora

are broader; highlights include recommendations to better share data; document significant assets that are unique or costly, as a first step in sharing infrastructure; and build in Atlantic-wide bartering mechanisms.

3.1.1 GO-SHIP

The Global Ocean Ship-based Hydrographic Investigations Program[38] (GO-SHIP) coordinates a network of globally sustained hydrographic sections as part of the global ocean/climate observing system including physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems. GO-SHIP provides approximately decadal resolution of the changes in inventories of heat, freshwater, carbon, oxygen, nutrients, and transient tracers, covering the ocean basins from coast to coast and full depth (top to bottom), with global measurements of the highest required accuracy to detect these changes.

Global hydrographic surveys have been carried out approximately every decade since the 1970s through various research programs but have lacked formal global organisation, leading to a lack of visibility for hydrography in the global observing system, a significant decrease in the number of trans-basin sections carried out by some countries, and sections being carried out without the full suite of core variables. The GO-SHIP Panel was established in 2007 to develop a strategy for a sustained global repeat hydrography program, and distinguishes between three levels of parameters (Table 4):

- Level 1 are of highest priority to fulfil the scientific objectives of the GO-SHIP cruises and are recommended for every cruise,
- Level 2 are highly desirable as augmentation and addition for the science objectives executed on GO-SHIP cruises and should be collected when feasible, and
- Level 3 are ancillary measurements that often benefit from being taken in conjunction with the core measurements and/or address a scientific question unique to the region but their collection should not interfere with sampling Level 1 or 2 parameters.

The network's advantages include measurements to the full depth of the water column over entire basins, the ability to measure a large suite of EOVs and to deploy a variety of standard and new instruments, methods and systems (as research vessels are used), and highly accurate data of reference quality.

In Task 2.1 (GO-SHIP), AtlantOS expanded present GO-SHIP spatial coverage, particularly in the South Atlantic, by working with other hydrographic efforts to ensure GO-SHIP data collection and handling standards, established a new coordination office for Atlantic hydrographic surveys to keep records of past and upcoming surveys and to identify and address data overlaps, duplications and gaps, and formed a Hydrography Coordination Team to provide guidance for hydrographic surveys.

Measurement	Level	Variables
Sensor-based (sensors on CTD frame)	1	temperature, salinity, oxygen, lowered ADCP
	2	transmissometer
	3	chlorophyll (ocean colour)
Underway (uncontaminated seawater line or hull-mounted sensor)	1	pCO_2, temperature, salinity, shipboard ADCP, bathymetry, meteorological data
Bottles (samples taken from Niskin Samplers)	1	salinity, oxygen, chlorofluorocarbons (e.g., SF_6)
	3	nitrous oxide (N_2O)
Inorganic Nutrients	1	NO_3/NO_2 , PO_4, SiO_3
Inorganic Carbon	1	total alkalinity, dissolved inorganic carbon, pH
	2	pCO_2, DOC/DON, DIC -^{13}C,^{14}C
	3	POC/PON, HPLC pigments

Table 4: Sample Parameters for GO-SHIP (full list on the GO-SHIP webpage[39])

[38] https://www.go-ship.org/index.html
[39] http://www.go-ship.org/DatReq.html

For 2030, GO-SHIP plans to have the core mission continued, with expansion to cover more EOVs. For example, several GOOS EOVs (e.g., bio-optic and bio-acoustic observations, underwater video profile, POC, pigments, and omics) are not currently level-1 parameters. GO-SHIP also plans to expand the number of associated lines (which can be shorter, but are more regularly observed).

	Present	Modest Improvement	What is Needed
Variables Measured	see Table 4	More level 2 variables as level 1 variables. Ensure all repeated lines are able to adequately measure all level 1 variables	Regular observations of more level 1 including omics, POC, pigments, underwater video
Accuracy	See GOOS EOV specification sheets	Increased accuracy of nutrients and pH	Increased and certified accuracy of all level 1 variables
Cost (annual)	€3.7M (Atlantic basin)	€9.8M (Atlantic basin)	
Geographic Coverage	All Atlantic		additional shorter, more regular lines
Rationale	see text		
Benefits	see text		

Table 5: Summary for GO-SHIP[40]

3.1.2 Ships of Opportunity Program (SOOP)

The primary goal of the Ships-of-Opportunity Programme[41] (SOOP) is to fulfil upper ocean data requirements, established by GOOS and GCOS, which can be met by measurements from ships of opportunity (SOO). The core scientific mission is improving coherence and coordination, coverage, quality, timeliness and data flow from the existing, formerly uncoordinated ship of opportunity networks (Carbon-VOS, SOOP and FerryBox).

The network of SOOP ships currently working in the North Atlantic provides a backbone of essential basin-wide observations of physical and biogeochemical parameters that cannot be measured by other means, including carbon parameters and nutrients, as well as SST and SSS ground-truth. These measurements enable, for example, monthly resolution of the net North Atlantic Ocean atmosphere CO_2 flux, accurate to better than 20% when integrated with ARGO, satellite and physical re-analysis data, provided that coverage is coherent and well-coordinated. This network supports other operational needs (e.g., in fisheries, shipping, defence) through the provision of upper ocean data for data assimilation in models and for various other ocean analysis schemes.

SOOP's key technology is instrumentation that can be installed on non-scientific vessels and run with minimal supervision: pCO_2 systems (allowing underway observation of surface ΔpCO_2, T, and S) and Ferrybox systems (measuring T, S, fluorescence and O_2). In addition, ships' officers are trained to deploy Expendable Bathythermographs (XBTs) at predetermined sampling intervals to acquire temperature profiles in the open ocean. The network's advantages include regular time series of surface and near-surface properties, an ability to measure some EOVs which cannot be measured from any other platform (e.g., carbonate variables pCO_2, alkalinity), global coverage, and free and open exchange of data and best practices.

In Task 2.2 (Ships of Opportunity Program (SOOP)), AtlantOS improved connectivity of these networks (shared infrastructure, data standards, protocols, a continuum of observations for key EOVs from the open ocean into the coastal realm, and utility for development of products). Specifically, the coverage of the

[40] personal communication, Toste Tanhua, Task 2.1 (GO-SHIP) lead
[41] http://www.jcommops.org/sot/soop/

network was extended (particularly in the South Atlantic: off Brazil, and off Argentina, but not yet off Africa) and instrumentation to add total alkalinity and pCOs as new EOVs were evaluated. Technical developments during AtlantOS included a new automated underway Total Alkalinity system, as well as a new Anderaa Optode pCO_2 detector.

For 2030, SOOP plans to put in place new and improved instrumentation for biogeochemical EOVs, to move to real-time and near real-time data availability (in some cases, the data is presently delayed by up to six months), and to redesign instrumentation to be more highly portable in order to overcome the threat due to rapid changes in the shipping industry. In particular, vessels now rarely commit to a single route for extended periods, and it is prohibitively expensive to continually re-install scientific instruments for short periods of time. SOOP will also work with the shipping industry to have scientific instrumentation integrated into ships when they are built.

3.1.3 Continuous Plankton Recorder (CPR) Survey

The Continuous Plankton Recorder[42] (CPR) survey is one of the most well established autonomous observing systems covering the North Atlantic basin-scale over multiple decades. The CPR is an autonomous instrument towed from ships of opportunity, primarily from the commercial shipping industry, that has been providing data for over 80 years, mainly for scientific research. The CPR survey in the Atlantic is part of a global programme called the Global Alliance of CPR Surveys (GACS), which includes sister surveys in the North Pacific, Arctic, Southern Ocean and Australia and New Zealand.

Each month, about 20 volunteer commercially-operated vessels, operating mainly in the North Atlantic, collect 20,000 km of high temporal and spatial biological data related to planktonic organisms in order to provide essential information on biodiversity and ecological changes in time and space. Data, more than 150 million records on about 1000 taxonomic entities, is freely available. The network has recently expanded to sample in the South Atlantic and other regions. It is also developing a centralised global CPR database and modernising the fleet with new autonomous instrumentation.

The core mission of the CPR Survey is to monitor the health of the oceans for scientists and policy-makers by providing the best biological, chemical, and physical data over large geographical areas in the pelagic realm in the most cost-effective manner. There is an increasing need to monitor the marine environment for legislative reasons (e.g., MSDF Good Environmental Status targets) and at reduced costs using autonomous methods. Therefore, there are obviously huge cost benefits in incorporating new technologies and sensors into existing infrastructures like the CPR survey to optimise and enhance the Atlantic observing system.

The key technology is a standard CPR body equipped with CTD sensors, multi-spectral fluorescence, $pC0_2$, water samplers, optical sensors (zoocam), and molecular tools for Harmful Algal Bloom, pathogen and virus detection. The network's advantages include semi-autonomous cost-effective monitoring over 20,000 km towed per month and over 1000 taxa routinely recorded for over 60 years, large spatial and temporal coverage at the ocean basin scale, and extremely reliable and robust scientific instrumentation.

In Task 2.3 (Continuous Plankton Recorder (CPR)), AtlantOS optimised and enhanced CPR surveys and made data freely available: it used new technology to develop a method to more rapidly determine zooplankton abundance; provided near-real-time sensors for variables such as pH and chlorophyll on CPR transects across coastal to open ocean waters; deployed CO2 sensors on shorter European routes in the English Channel to provide additional data on real-time productivity; and implemented faster quantitative molecular assays of key harmful and pathogenic organisms. The CPR Survey also created new ecoregions using physical and biological data – and wants to monitor each of these ecoregions in a more systematic and targeted way.

[42] https://www.cprsurvey.org/

For 2030, the CPR Survey plans to continue to adopt new technologies into its existing programme, including biogeochemical sensors, optical technologies and molecular tools, and to secure core international funding for the open ocean routes, which are not funded by national bodies but which are the most important, scientifically. They are exploring more systematic coverage in the North Atlantic, particularly in relation to ecoregions. Within the Global Alliance, the CPR Survey is also developing new surveys in the South Atlantic and Indian Oceans to create global coverage.

	Present	**Modest Improvement**	**What is Needed**
Variables Measured	>1000 taxonomic species/entities (phytoplankton and zooplankton). Basic physical measurements (e.g. temperature, salinity), marine microplastics	Standardised CTDF and other sensors on all CPR bodies	Biogeochemical sensors, optical technologies and molecular tools
Platform Type and #	~ 20 CPR bodies, basic CTDs	Standardised CTDF and other sensors	Biogeochemical sensors, optical equipment and molecular facilities.
Accuracy		Improved sensors	Improved sensors and accuracy. Increased taxa identification from molecular tools
Cost (annual)	€2.0 million (N. Atlantic)	~€3.5 (N. Atlantic)	Depends on option
Geographic Coverage	20, 000 km towed per month in North Atlantic, none in S. Atlantic	Increased coverage including all ecoregions of the North Atlantic (e.g. Arctic regions).	More systematic coverage in N. Atlantic (covering all ecoregions); S. Atlantic coverage (under development)
Rationale	Improved understanding of environmental impacts (e.g. climate, acidification) on biological communities	Increased geographical coverage and instrumentation	Vastly improved sensors and increase in biological entities monitored. Increase speed in biological analysis
Benefits	Biological EOV/EBV for GOOS and GEOBON ; ocean health monitoring ; biological indicators of state (MSFD requirements) ; Climate Change impacts ; ocean acidification; Harmful Algal Blooms and pathogens; fishery productivity indices; carbon sequestration indicators ; monitoring of biodiversity and invasive species	Improved coverage and accuracy. Improved physical sensors to compliment biological data	Vastly improved biogeochemical sensors complimenting Argo and other monitoring programmes. Molecular tools to assess all biological changes and detection of Harmful Algal Blooms, pathogens and invasive species. Optical technologies to autonomise plankton identification

Table 7: Summary for CPR[43]

[43] personal communication, Martin Edwards, Task 2.3 (Continuous Plankton Recorder - CPR) lead

3.1.4 Fisheries and Zooplankton Observations

The core mission of fisheries and zooplankton observations is to measure the abundance and distribution of fish and zooplankton and to provide quality-controlled acoustic data in support of conservation of these species and management of fisheries. In European waters, data collection is funded mainly through the Scientific, Technical and Economic Committee for Fisheries (STECF) of the European Commission, so cost estimates for the programme are not readily available. The STECF assists the Commission in the preparation of legislative proposals, delegated acts or policy initiatives and monitors the evolution of policy to bring about an exchange of experience and good practice.

The key technologies are calibrated echo-sounders and trawl sampling gear. The network's advantages include that fact that it is well coordinated through ICES and other organisations/projects, and that there is an international agreement on metadata convention for acoustic data and developed software to analyse the acoustic data and produce zooplankton and fish indices.

In Task 2.4 (Fisheries and zooplankton observations), AtlantOS has improved the fish survey data availability through the ICES data center for three key pelagic fisheries surveys; the ICES data center previously did not host acoustic and trawl data from pelagic surveys). AtlantOS work also prepared the ICES data center to host these data in accordance with ICES and international data standards and modified current processing and analysis software to fit into the new system. The result is a fish survey database available through an open source, freely accessible Acoustic Trawl Survey Data Portal and which is compatible with the ICES metadata standards recently implemented throughout the North Atlantic.

For 2030, there are plans to standardise formats for raw data (to improve sharing of acoustic raw data to, for example, estimate mesopelagic layers) and to define an EOV based on acoustic data. Currently, there is no infrastructure to host acoustic raw data or acoustic-related EOVs, so additional work with ICES on data management will be required. What is ultimately needed is to define an EOV based on acoustics, which will enable better estimates of mesopelagic layers.

3.1.5 Seafloor Bathymetry

Seafloor bathymetry plays a crucial role in the marine environment and beyond. Oceanic circulation, for example, influences climate dynamics and plays a key role in model predictions. Bathymetric data is also important for safety of navigation, deep-water forensics, marine infrastructure development, habitat classification and much more. It is essential to protect the marine realm, to establish sustainable ocean management, and to achieve the United Nations' Sustainable Development Goals. Nevertheless, high-resolution bathymetric data exists for less than 20% of the ocean floor.

EuroMapApp[44], the seafloor-mapping task, uses multi-beam echo-sounders (MBES) to record bathymetry, backscatter imagery, and water column data in order to map the world's oceans and produce a global ocean bathymetry. The network's advantages include good international integration and collaboration, and connections to several regional and international open access data repositories and to the Seabed2030 project that aims to map the world's ocean floors by 2030. It is estimated that completing the mapping for depths greater than 20m at 100m spatial resolution will cost $3 billion and take 1000 ship years, though the use of autonomous vessels and crowdsourcing should reduce these figures.

In Task 2.5 (EuroMapApp), AtlantOS established "underway bathymetry", in which European research vessels collect bathymetric data during their transit routes. AtlantOS also compiled European deep seafloor mapping results in the high seas from several countries. These data have been integrated into the IHO Data Centre

[44] https://sextant.ifremer.fr/eng/Donnees/Catalogue#/metadata/43a2dc55-1c49-4ecf-8d07-91a9a0eccff2

for Digital Bathymetry (DCDB), where they are archived and available for everyone. The repository allows direct access to the data and immediate visualization of the seafloor. These data can, for example, be used by bathymetrists and scientists from other fields for their research, NGOs for designating and monitoring marine protected areas, and also by the marine industry for infrastructure planning and development. Forthcoming datasets (from Atlantic transits, for example) will be continuously integrated into this repository. Furthermore, a gap analysis has been performed within AtlantOS, identifying target areas in the North Atlantic that should be mapped next; one of these areas has since been mapped by NOAA's Okeanos Explorer.

For 2030, plans are to expand the underway bathymetry to other research and survey vessels, promote technology developments to make mapping for efficient and cost-effective, establish applications to show surveying vessels where the data gaps are (work in progress), and perform gap analysis on a global scale to outline high-priority regions for future mapping surveys as a basis to formulate observing strategies. The ultimate goal is to produce a definitive, high-resolution bathymetric map of the entire World Ocean by 2030.

	Present	**Modest Improvement**	**What is Needed**
Variables Measured	Bathymetry	More nations perform transit mapping; more researchers / institutions make their data publicly available	More commitment to FAIR principles for bathymetric data
Platform Type and #	Research vessels (1-2 per year in dedicated survey)	Have 30 vessels do transit mapping	Autonomous mapping systems (especially low-budget solutions); efficient mapping strategies
Accuracy	100m - 1km	50m – 1km	≤50m
Cost (annual)	€1 million	Transit mapping and data sharing is practically free	
Geographic Coverage	less than 20% at 100m	50% at 100m would be great, 100% better	More mapping systems at sea
Rationale	safety of navigation, deepwater forensics (e.g., MH370), geohazards, marine conservation, marine infrastructure development		
Benefits	Large-scale and some medium to small-scale structures are identified on the seafloor	More medium to small-scale structures will be discovered on the seafloor	Complete high-resolution and publicly available bathymetric map of the Atlantic Ocean gives a coherent picture of the seafloor and can be used in a variety of applications

Table 8: Summary for Seafloor Bathymetry[45]

3.1.6 'Omics

'Omics refers to biological analysis at the molecular level (i.e., DNA, RNA, or proteins) to identify organisms and their activities (related to, for example, carbon, oxygen, metals, toxins, and nutrients). It is an emerging field with many techniques, including genomics (the study of the structure, function, evolution, mapping, and editing of the genome), proteomics (the study of proteins), and metabolomics (the study of chemical processes involving the small molecule intermediates and products of metabolism, which are often chemical fingerprints identifying cellular processes).

[45] personal communication, Anne-Cathrin Wölfl and Colin Devey, Task 2.5 (EuroMapApp) members and lead

The mission of the Global Omics Observatory Network (GLOMICON)[46] is to organise "omically enabled observatories and create an integrated, global system of multi-omic monitoring to enhance our capacity to understand, investigate, and monitor the biosphere." 'Omic techniques can be incorporated in existing observation programmes and platforms – the CPR Survey, for example, has added molecular sensors to detect, identify, and measure viruses and cells.

The main advantage of the 'omics techniques lie in their ability to mainstream biological and ecological monitoring by making it quicker and easier to distinguish, among other things, microbes, cell types, and biological processes. There is a need for greater coordination with existing networks, particularly in biology, including MBON, the Ocean Biogeographic Information System (OBIS), and the Global Biodiversity Information Facility (GBIF). Co-leadership with GOOS' biology/ecosystem panel will foster integration with existing observation programmes by, for example, establishing links to EOVs and establishing standards and inter-calibration processes.

3.1.7 Argo

The global Argo network is an array of approximately 4,000 floats, distributed over the global oceans at an average 3-degree spacing, that annually provide 140,000 temperature and salinity (T&S) profiles, as well as velocity measurements. Core Argo profiling floats cycle to a depth of 2,000m every 9-10 days with each float having a 4-5 year lifetime. About 2% of the profilers go below 2000m (see Deep Argo, below) and 9% contain at least one biogeochemical sensor. In the AtlantOS domain, there are currently about 850 active Argo floats; maintaining this coverage requires the deployment of approximately 250 new floats each year. The European contribution to Argo is coordinated through the Euro-Argo[47] ERIC (European Research Infrastructure Consortium[48]) signed by 12 countries with the goal to sustain ¼ the global array.

Although core Argo can be considered mature in terms of technological readiness level, the newly formed global Biogeochemical-Argo array as a coordinated observing network remains in the pilot stage, and there are currently a limited number of floats with biogeochemical sensors deployed. Biogeochemical Argo is set to enable direct observation of the seasonal to decadal-scale variability in net community production (NCP – the amount of biologically-produced organic carbon that is available to be exported out of the surface ocean), the supply of essential inorganic nutrients transported from deep waters to the sunlit surface layer, ocean acidification, hypoxia, and ocean uptake of carbon dioxide. Bio-optical sensors would supplement Ocean Colour satellite observations by providing measurements of chlorophyll, light, and light scattering deep into the ocean interior throughout the year, in cloud- and ice-covered areas, or during the dark of polar winter. The present number of Biogeochemical Argo floats is insufficient to resolve many of the phenomena on basin scales. Until a denser network is developed, they should be viewed as providing high spatial and temporal data on local to regional scales (1 – 1000 km), which are complementary to the basin scale, decadal scale ship-based repeat hydrography observations.

The key technology of the Argo programme is the autonomous profiling float, which can house a wide variety of sensors. Its core scientific mission is to provide essential in-situ data for operational re-analysis and forecasting, and for assessment of the state and variability of the climate system with respect to physical, biogeochemical, and ecosystems parameters. The network's advantage in meeting this objective is a cost-effective and robust technology, which can provide data for 4-5 years at costs-per-profile a small fraction of ship-based profiles.

[46] https://sites.google.com/view/glomicon/home
[47] https://www.euro-argo.eu/
[48] https://ec.europa.eu/info/research-and-innovation/strategy/european-research-infrastructures/eric_en

In Task 3.1 (Argo evolution), AtlantOS extended the core Argo mission towards the deep ocean and towards biogeochemistry by developing more cost-effective platforms and testing the implementation of new sensors (e.g. pCO_2 optode); produced a consistent Argo and Bio-Argo validated dataset for the Atlantic Ocean with a specific focus on deep CTD, oxygen data, chlorophyll a, backscattering, and nitrate data; and addressed the future sustainability of the Bio-Argo and Deep-Argo components of the Argo programme by developing international partnership and long-term agreements with Euro-Argo members for organisation and funding.

For 2030, Argo plans to strengthen the extension to high latitude of the original mission (T and S to 2000 m), which is otherwise in good shape in the open ocean; there are also plans to increase density in marginal seas and western boundary current. In addition, the biogeochemistry (BGC Argo) and deep (Deep Argo) extensions are to be fully implemented, with 1000 BGC floats and 1200 deep floats among the 4700 floats globally. The BGC Argo mission is in the pilot phase – the technology and sensors are ready, but sustained funding is required. Deep Argo is in the early pilot phase, with technical work on both the sensors and the float ongoing.

	Present	**Modest Improvement**	**What is Needed**
Variables Measured	T&S (0-2000m) Deep T&S (below 2000m) BGC: 02,Chl-a, bbp, pH, NO3, downwelling irradiance	T&S (0-2000m) Deep T&S (below 2000m) BGC: 02,Chl-a, bbp, pH, NO3, downwelling irradiance	T&S (0-2000m) Deep T&S (below 2000m) BGC: 02,Chl-a, bbp, pH, NO3, downwelling irradiance
Platform Type and #	900 operating floats including 20 deep and 30 BGC 10% of floats have O_2 sensors **Deployment per year** Core 260 Deep 10 BGC: 15	900 operating floats including 100 deep and 100 BGC 30% of floats with O_2 sensors **Deployment per year** Core floats 230 Deep float 35 BGC: 35	900 operating floats including 225 deep and 225 BGC 50% of floats with O_2 sensors **Deployment per year** Core floats 150 Deep float 75 BGC:75
Accuracy		Accuracy of the sensors below 2000m need to be assessed. Stability of the BGC parameters over 5-year timeframe need to be assessed.	
Cost (annual) **Equipment**	6 508 500 €	9 150 500 €	12 226 500 €
Cost (annual) **Data Management**	650 850€	915 050€	1 222 650€
European Share: (50% of total)	3 579 675 €	5 032 775 €	6 724 575 €
Geographic Coverage	Open ocean and marginal seas	Open ocean and marginal seas	Open ocean and marginal seas

	Present	Modest Improvement	What is Needed
Rationale	Explained in Euro-Argo Strategy for next decade https://doi.org/10.13155/48526		
Benefits	• Climate change monitoring • Operational oceanography • Ocean health monitoring • Research	• Better assess climate change impacts over the whole water column • Better constrain physical and ecosystem operational models • New fields in Research	• Better assess climate change impacts over the whole water column • Constrain physical and ecosystem operational models • New fields in Research

Table 9: Summary for Euro-Argo[49]

3.1.8 OceanSITES

OceanSITES[50] is a series of coordinated moored arrays, which record the temporal evolution of multidisciplinary properties covering the surface ocean and adjacent atmosphere, the water column, and the seafloor. OceanSITES provide a truly Eulerian view of ocean phenomena. The installations use automated systems with advanced sensor technology, yielding high temporal resolution, and often provide data in real-time. OceanSITES sites create long records of highest-quality data. The sites serve multiple purposes defined by the regional and global needs. The three main objectives for operating the sites are:

- Multidisciplinary Global Ocean Watch (Task 3.2 - OceanSITES biogeochemistry) – these sites aim for long time series of properties across disciplines (physics, biology/ecosystem, biogeochemistry), and may also include calibration/validation components for satellite ocean colour products.
- Transport Mooring Arrays (TMA), (Task 3.3 - OceanSITES transport) – these sites monitor transport and characteristics (physics, biogeochemical, ecosystem) and also serve as calibration/validation sites for satellite altimetric transport comparisons.
- Air/sea flux reference sites (In part represented in Task 3.5 - PIRATA) – these sites have complex surface buoys accompanied by upper ocean instrumentation (including gas exchange) and serve as calibration/validation sites for, for example, satellite-derived products related to weather and wave forecasting.

OceanSITES time series data is needed to provide both monitoring and process observations with a temporal resolution from minutes to decades. Based on these, we can detect, understand, and predict global physical, biogeochemical and ecosystem state and changes, including ocean warming, ocean carbon uptake and storage, and acidification. The biogeochemical measurements from the OceanSITES network, for example, provide a series of fixed-point time series of zooplankton, phytoplankton, particles, and meta-genomic diversity. These data enable assessments of the structure and function of biological communities, addressing a major observational gap in variables central to Europe’s Marine Strategy Framework Directive, including impacts due to ocean acidification and pollution by microplastics and other hydrocarbons.

The key technology is a mooring (some in the deep sea) carrying autonomous sensors and samplers. The core scientific mission is the provision of time series at fixed locations, including (mass, heat, and freshwater) fluxes, and other EOVs. The network has several advantages: the use of established and robust technologies, long-term time series, sensors can be large and have high power demands, high-frequency multidisciplinary data, the ability to operate in highly-advective environments and in bad weather, coverage of the full water column, and the ability to provide samples.

[49] personal communication, Sylvie Pouliquen, Task 3.1 (Argo Evolution) lead
[50] http://www.oceansites.org/

AtlantOS enhanced data management by standardizing variables across the networks and linking with other observing systems and upgraded capability by integrating sequential zooplankton samplers and sediment traps. AtlantOS also further developed and integrated the network of Atlantic TMAs, extended measurements to the near-surface ocean (to deliver critical, climate relevant upper ocean fluxes), and ensured a more coherent survey of non-physical EOVs, including adding oxygen sensors to existing moorings to coherently monitor the overflow water masses at four key TMA sites. AtlantOS identified as a major shortcoming the timely availability of TMA data and demonstrated the implementation of subsea real-time data telemetry systems to address this issue. AtlantOS also addressed the inhomogeneity among the different TMAs (a challenge to their sustainability) by increasing cooperation between the 20 different network operators through a common website which provides common documentation, guidelines, and products.

While the core science mission is covered in the AtlantOS region, expansion is essential, particularly in the South Atlantic, to more properly represent ocean state and trends in the Atlantic. For 2030, the network plans to increase spatial coverage (including to shelf seas and in regions of complex topography) and to enhance sensors and samplers to address current and future EOVs, including in the emerging field of ‘omics. There are plans to use models to optimise the location of these moorings[51].

	Present	Modest Improvement	What is Needed
Variables Measured	**Multidisciplinary Global Ocean Watch:** • Sites at well-chosen locations (FRAM, PAP, Labrador Sea, OOI, BATS, CVOO)	Include/start new sites addressing emerging challenges in cross disciplinary observing (deep biodiversity, seamounts) Augment long term study sites with ‘omics samplers	
	Transport Moored Arrays: • Topographic control: FRAM, GSR Arrays, Vema Channel, • Basin-wide Overturning arrays: OSNAP, AORC, NOAC, RAPID, • Boundary Current arrays (Fram Strait, GSR, 53°N Array, MOVE, RAPID, OSNAP Greenland, 11°S, SAMBA / SAMOC)	Establish new sites at important locations: • Strait of Gibraltar, Charly-Gibbs-Fracture-Zone, • Selected eastern Boundary Arrays (particularly eastern Boundary Augment TMA sites with biogeochemical sensors for baseline and continuous tracer flux estimates (e.g. oxygen, carbon, nutrients)	T&S, velocity, density observations must be augmented with biogeochemical sensors (oxygen, carbon, nutrients) and biology seensors (passive and active acoustics; omics)
	Air/Sea flux reference sites: • Climate quality air/sea flux sites:	Additional sites in key regions:	• Full set of flux (heat, momentum)

[51] https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.13152

	NTAS, PIRATA, OOI Irminger Sea, CVAO (Island)	• Western Boundary Currents (incl. Gulf Stream) • Deep convection sites: Labrador Sea, • Agulhas Retroflection	instrumentation following climate data specifications • quality upgrade of some sites
Accuracy	Climate (see WIGOS spec)	Climate (see WIGOS spec)	Climate (see WIGOS spec)
Cost (annual)	200.000 € per mooring		300.000 €
Geographic Coverage	Selected sites at locations justified by the observing objectives	Refined additional sites at selected locations	Enhance the multi-disciplinary time series observing Better coverage in the South-Atlantic. There is e.g. no basin-wide transport array in the southern hemisphere.
Rationale	See GOOS network specification sheet; Send et al.; Cronin et al.; GCOS implementation plan		
Benefits	• Climate change monitoring • NWP & Operational oceanography • Ocean health monitoring • Research • Cal/Val in-situ satellite observing • Cross themes (biology, biogeochemistry, atmosphere, ocean) process and long term observing • Deep ocean observing	• Cross themes (biology, biogeochemistry, atmosphere, ocean) climate monitoring • Improved NWP and Operational oceanography • Research • Cal/Val in-situ satellite observing • Cross themes (biology, biogeochemistry, atmosphere, ocean) process and long term observing	• Model/observation metrics • Development of parametrizations • Constrain physical and ecosystem models • Research for improved prediction

Table 10: Summary for OceanSITES[52]

3.1.9 Gliders

Underwater gliders are low energy consumption, remote controlled, autonomous platforms particularly suited to sample mesoscale and sub-mesoscale ocean processes key to the physical, chemical and biological oceanography close to ocean boundaries, where they are difficult to observe by other methods. In addition,

[52] personal communication, Ursula Schauer , Task 3.2 (OceanSITES biogeochemistry) and Task 3.3 (OceanSITES transport) member

they offer enhanced capabilities (i.e., manoeuvrability and position control) compared with profiling floats. The gliders perform sawtooth trajectories from the surface to depths of 1000-1500m, along reprogrammable routes (using two-way communication via satellite), and can be operated for a few months. Their role in the integrated observing system is to fill the gaps left by other observing platforms. An emerging network, the glider network is coordinated internationally through the OceanGliders Steering Team and within Europe by the EuroGOOS Glider Task Team[53]; there are between five and seven EU gliders in operation at any one time in the Atlantic Ocean, all with BGC sensors.

The mission of the EGO[54] (Everyone's Gliding Observatories) underwater glider network, initiated by European scientists, is to develop a new observational capacity for process studies and operational monitoring of ocean physics and biogeochemistry with gliders. In particular, gliders could be deployed to sample most of the western and eastern boundary circulations and the regional seas of the Atlantic (which are not well covered by the present ocean observing system) and in the vicinity of fixed-point time series stations. Gliders can operate at higher resolution than Argo profilers or even more sparsely distributed ship-based observations. Therefore, glider-based observations have a great potential to address regional and coastal issues, which are so important for societal applications.

The key technologies behind the glider network are autonomous underwater vehicles, miniaturised sensors, and two-way satellite communication. The network's advantage is it is a cost-effective, robust, and unique tool to fill present observational gaps, with programmable and flexible temporal and spatial coverage and sampling strategies.

In Task 3.4 (Gliders), AtlantOS developed an application for outreach and public dissemination of glider data that also met the more complex set of requirements to make glider piloting easier. The application is a web service which stores and makes glider data available and allows pilots to create and manage missions, including pilot logs and tracking changes to mission parameters. AtlantOS also demonstrated that gliders can be an effective method to minimise observational gaps between the coast and the open ocean, particularly in the eastern boundary of the Atlantic Ocean, and noted that the rapid development of (e.g., biogeochemical and biological) sensors will enhance the use of gliders with regard to the assessment of fisheries, particularly in regions that are at risk from anthropogenic pressure and therefore depend on marine resources.

For 2030, the emerging network plans to establish its core mission (OceanGliders) by securing human capacity and resources and investment in instrumentation, including better management of BGC sensors and the inclusion of newer technologies. They also are planning a future expansion of the core mission to reach an optimal coverage (in time and space) of targeted phenomena (i.e., boundary currents, storms, water transformation). The rationale is to address issues at regional scales and also to support research and operational applications (e.g., forecasting and analysis) and the monitoring of satellite missions.

3.1.10 PIRATA

The Prediction and Research Moored Array in the Tropical Atlantic[55] (PIRATA) was designed to study ocean-atmosphere interactions in the tropical Atlantic that affect regional weather and climate variability on seasonal, interannual, and longer time scales. It was established in 1997 through a collaboration between Brazil, France, and the United States, and has undergone expansions and enhancements since 2005 to improve its utility for ocean and climate research and forecasting. Targets for the Atlantic Ocean include the maintenance of the 18 moored buoys in the PIRATA array. Ocean-atmosphere interactions in this region influence the development of droughts, floods, severe tropical storms and hurricanes, with impacts felt by millions of people in the Americas and Africa.

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[53] http://eurogoos.eu/gliders-task-team/
[54] https://www.ego-network.org/
[55] http://www.brest.ird.fr/pirata/index.php

The network's key technology is ocean-met buoys and ADCP moorings. The core scientific mission is monitoring ocean-atmosphere interactions in the tropical Atlantic Ocean in support of climate research and process studies. The network's main advantage is the ability to measure key parameters (including EOVs) at fixed locations and to transmit them in real-time.

In Task 3.5 (PIRATA), AtlantOS improved the efficiency and relevance of PIRATA by adding additional sensors to fill observational gaps and demonstrate a "future PIRATA network." Specifically, AtlantOS upgraded PIRATA moorings by adding a variety of key physical (conductivity, current), meteorological (P_{atm}, long-wave radiation), and biogeochemical (O2, CO2) sensors, upgraded the data management system with a strong focus on new biogeochemical sensors (O2 and CO2), and worked to improve the long-term sustainability of the upgraded PIRATA system through international partnerships, including non-EU countries (e.g. Brazil, USA, and South Africa).

For 2030, the network plans to continue the present network and yearly cruises to service the instrumentation (though there is some danger that ship-time might become an issue), with some planned enhancements, including replacing the Atlas systems with T-Flex systems). Possible future expansions include increasing the number of EOVs measured in the mixed layer, including biogeochemical EOVs (such as CO2 and O2), as well as more buoys. Among the challenges are commitments from new partners, and human capacity to work at sea and manage the data.

	Present	Modest Improvement	What is Needed
Variables Measured	<u>From fixed met-ocean moorings:</u> 1) Atmospheric: Wind velocity speed and direction, air temperature, relative humidity, rain, Shortwave radiation, Longwave radiation (at some points), Barometric pressure (at some points) 2) Oceanic (0-500m depth): sea surface and subsurface temperature and conductivity; pressure (300 and 500m); currents (at 10m at some points). 3) Biogeochemistry: surface pCO2 (at 3 points); O2 (at 300m & 500m at 3 sites) <u>From ADCP moorings:</u> Equatorial currents at 23W, 10W and 0E, surface-300m depth. <u>From yearly servicing cruises:</u> 1) CTDO2 & XBT profiles, sea water samplings for analysis (S, O2, nutrients etc.); SST/SSS from TSgraph; currents from Vm-ADCP. 2) Contribution to Argo & GDP/DBCP: deployment of Argo profilers and SVPs.	<u>Funded and planed:</u> Enhancement of vertical resolution for C in the northwest. Network fully equipped with T-Flex systems (going on; T-Flex replacing ATLAS system). <u>Wished:</u> 1) Enhancement of vertical resolution in the mixed layer for T, C and currents. 2) Enhancement with biogeochemistry parameters (CO2, O2, pH, AT). 3) Enhancement with Longwave radiation and Barometric pressure 4) Additional moorings (in the South Atlantic and the NorthWest tropical Atlantic).	 Funding Funding & partners Funding Additional partners to ensure funding & servicing

			(vessel time)
Platform Type and #	ATLAS and T-FLEX fixed moorings at 18 sites: 38W: 20N, 15N, 12N, 8N, 4N; 35W-0N; 30W-8S; 32W-14S; 34W-19S; 23W: 20N, 12N, 4N, 0N; 10W: 0N, 6S, 10S; 0E-0N; 8E-6S		
Cost (annual)	5.2M€ (shared between USA, Brazil, France), including 4.3M€ for vessel time.		
Geographic Coverage	Tropical Atlantic: Latitude: 20N-10S Longitude: 38W-8E		
Rationale	Improved understanding of ocean-atmosphere variability in the tropical Atlantic		
Benefits	- PIRATA data are supplied in real-time to customers in operational weather, climate, and ocean services. - Data transmitted in real-time allow to address fundamental scientific questions as well as societal needs - PIRATA data (moorings and cruises) and science allow to improve prediction of weather and climate variability and their impacts, but also to assess the impacts of ocean warming, sea level rise, extreme weather events, deoxygenation, ocean acidification, marine ecosystems, living marine resources, and pollution.		

Table 11: Summary for PIRATA[56]

3.1.11 Surface Drifters

Lagrangian drifting buoys (drifters) are equipped with a thermistor on the base of the surface hull to measure sea surface temperature (SST) and a drogue centred at 15m below the surface which causes the drifter to follow the surface circulation. The global network of drifting buoys is coordinated by the Data Buoy Cooperation Panel (DBCP) under the Joint WMO-IOC Commission for Oceanography and Marine Meteorology (JCOMM).

The objectives of the global drifter network are to maintain a global 5x5 degree array of satellite-tracked surface drifting buoys (about 1250 throughout the world's oceans, 320 in the Atlantic) to provide an accurate and globally dense set of observations of mixed layer currents, sea surface temperature and atmospheric pressure, and to provide a data processing system to deliver the data to operational and research users.

[56] personal communication, Natalie Lefevre, Task 3.5 (PIRATA) member

Hourly measurements allow the diurnal cycle of temperature to be resolved. Approximately 50% of the drifter array, mainly in mid-latitudes, are equipped with barometers to measure sea-level atmospheric pressure. The drifters have a lifetime of about 1.3 years in the Atlantic, although this is reduced to about 0.9 years in the tropical Atlantic, so there needs to be roughly 320 deployments in the Atlantic every year to maintain coverage.

The key technology for this network is a well-proven sock drogue tracking currents at 15m depth and equipped with satellite communication. The core scientific mission is measuring ocean surface currents and weather. The main network advantage is a cheap, expandable platform that can remain at the surface, taking hourly measurements.

In Task 3.6 (Surface Drifters), AtlantOS enhanced the drifter network, with the objective of maintaining this upgraded observation system over the long-term, by strengthening activity in the South Atlantic (where the density of drifting buoys, most especially east of 20°W, appears low in comparison to the North Atlantic, see project deliverable D3.20[57] – "Drifter network improvement report"), and by developing drifters with enhanced measurement capability to fill observational gaps. In particular, new salinity drifters (low-cost and resistant to bio-fouling) were developed (see project deliverable D3.4[58] – "Design a buoy fitted with a low cost salinity sensor"). Data collected by bathythermic string drifters (for temperature profiling of the ocean boundary layer) were reviewed in the AtlantOS project, and deliverable D3.5[59] ("Development of bathythermic string drifters") reported that "the drag caused by the chain and its interaction with currents make it difficult to exploit the data for current estimation," thereby suggesting that such platforms are probably incompatible with the primary mission (current estimation).

For 2030, the network plans to fit all drifters with barometers (requires formal NOAA – EUMETNET collaboration, but no additional funds), expand the core mission to include high-resolution SST to calibrate / validate satellite measurements, outfit some of the drifters with SSS (though technological robustness has yet to be demonstrated) and some with fish acoustic tag receivers (and demonstrate efficiency).

	Present	**Modest Improvement**	**What is Needed**
Variables Measured	• SST • Surface currents • Air Pressure (AP) for some	AP on all drifters in the North and Tropical Atlantic	• High-resolution SST for a few • SSS for a few
Platform Type and #	Approx. 250 SVP* and 350 SVP-B** in the AtlantOS area	Reduce the number of SVP and increase the number of SVP-B in the N. Atlantic and Tropical Atlantic	

[57] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D3.20.pdf
[58] https://www.atlantos-h2020.eu/download/deliverables/3.4%20Design%20a%20buoy%20fitted%20with%20a%20low%20cost%20salinity%20sensor.pdf
[59] https://www.atlantos-h2020.eu/download/deliverables/3.5%20%20Study%20of%20the%20potential%20for%20existing%20bathythermic%20string%20drifters.pdf

Accuracy	• 0.3 K • 1 cm/s • 0.3 hPa		• 0.05 K • 0.05 psu
Cost (annual)	(estimated) 1.3M€	No cost	+400k€ for 100 platforms equipped to measure SSS or high-resolution SST
Geographic Coverage	Better coverage in N. than S. Atlantic, gaps in Tropical Atlantic, South Atlantic, and Labrador Sea		
Rationale	• Ocean studies • Numerical Weather Prediction (NWP) • Ocean circulation, satellite altimetry	NWP	Satellite cal/val for salinity missions and climate monitoring (to track subtle variations of SST)
Benefits	Direct societal benefits via research and NWP	Direct societal benefits via NWP	Societal benefits via climate monitoring

Table 12: Summary for Surface Drifter (* SVP: Surface Velocity Program – Lagrangian drifter tracking current at 15m depth; ** SVP-B (SVP-Barometer) – adds air pressure measurements)[60]

3.1.12 European Tracking Network

The Ocean Tracking Network (OTN) is a world leader in the use of acoustic telemetry and currently maintains the world's two most extensive telemetry lines in the western Atlantic continental shelf, and also has coastal deployments in South Africa and Angola, and is developing one for Brazil. OTN and its partner systems (e.g. gliders) have created mutually compatible data storage systems. Phase I of the European Telemetry Network (ETN)[61] brought European researchers together to start a European-based network, which deployed receivers on platforms (e.g., on PIRATA and gliders) and launched an ETN database, featuring over 57 million detections. Funding for Phase II (beginning April 2019 and running for four years) has been secured.

The key technology is acoustic telemetry, though the network plans to expand its focus to other telemetry technologies (e.g., satellite telemetry) in the future. The core scientific mission is to provide ocean information to managers and policy-makers relevant for ecosystem-based management. To accomplish this, European researchers are working more closely to increase and share infrastructure, data, and tagging of valuable species. The network's advantage is that its receivers can be attached to a variety of platforms (including buoys and gliders), rapidly expanding the network.

In Task 3.7 (European Animal Telemetry Network (EATN)), AtlantOS worked to incorporate Europe into the developing global telemetry network by integrating European efforts through the European Tracking Network and developed technical standards and best practices for European lines and species of interest. A key objective is to leverage resources for European researchers to acoustically tag valued species – to this end, AtlantOS worked with other tasks of AtlantOS (e.g. gliders, buoys) to develop joint studies and add acoustic receivers to existing infrastructure.

During Phase II, the network is planning to enhance its governance, to increase its membership, and to extend the network geographically, focusing on key locations and gates and on key species. The network already

[60] personal communication, Paul Poli, Task 3.6 (Surface Drifters) lead
[61] http://www.lifewatch.be/etn/

covers sites in EU rivers, estuaries, along the coast, and in the open Atlantic Ocean (including seamounts). By 2030, ETN plans to further increase spatial coverage across Europe and the Atlantic, to increase animal-borne environmental observations, and to incorporate a wider range of telemetric technologies (acoustic, satellite, and data storage) and platforms (e.g., fixed and autonomous vehicles).

	Present (Phase I)	**Modest Improvement (Phase II)**	**What is Needed (Phase III)**
Variables Measured	Spatio-temporal 2D/3D detection of aquatic species	Spatio-temporal 2D/3D detection of aquatic species, including some advanced movement and environmental (animal-borne) observation	Increased spatial coverage of aquatic species including advanced movement and environmental (animal borne) increased ocean observation
Platform Type and #	Focused on acoustic telemetry by some European researchers	Network to incorporate more European researchers and EU funded research infrastructure (fixed) acoustic receivers and transmitters) in strategic locations across the Atlantic and adjacent seas	Advanced European tracking network with long-term funded research infrastructure incorporating a range of telemetric technologies (acoustic, satellite, data storage) and platforms (fixed, AUV)
Accuracy	100s of m (acoustic) to 10s of km (satellite)	1-10 m (acoustic)	
Cost (annual)	1 500 000€	7 500 000€	25 000 000€
Geographic Coverage	Mainly focused on coast, estuaries, and rivers	Focused on strategic coastal locations (gates) and selected key species	Regional networks leveraged around strategic locations; all key species
Rationale	Variations in short to medium-term local spatio-temporal movements and survival of aquatic species	Variations in medium-term cross-border to regional movements and survival of aquatic species;	Variations in medium to long-term cross-border to regional movements and survival of aquatic species and response to human- and climate-driven pressures;
Benefits	Capacity building and enhanced collaboration (including data sharing) between European telemetrists	Demonstration of improved management and conservation in key species (highly mobile, migratory, anadromous, and marine species); some support and training of students and technicians; improved science (standardisation of data protocols and management)	Improved management and conservation of a wide array of species and wider spatio-temporal scales; widespread support and training of students and technicians; improved cross-disciplinary science and ocean obs.

Table 13: Summary for European Tracking Network[62]

[62] Personal communication, Francisco Hernandez, Task 3.7 (European Tracking Network) member.

3.2 Integration with Coastal Ocean Observing

Internationally-organised observing programmes, traditionally focused on the open ocean, are, for a variety of reasons, more coordinated at local or national levels in coastal regions. The nearshore is indeed too shallow, for example, for Argo profilers to be of much use, and satellite observations are, for some variables, masked or noised near the coast. At the same time, coastal observations have typically been driven more by local interests and capacity, which, for example, often results in less data sharing. Thus, the coastal and open ocean observing communities have not, for the most part, seen the benefits of integration, even though the ocean and coastal environments impact each other strongly; coastal processes, including mixing, upwelling, and terrestrial runoff affect the physics, biogeochemistry, and biology offshore, and sea-level rise from the open ocean impacts coastal regions. As outlined in AtlantOS Deliverable 4.5[63] ("Gap Analysis of Links Between Coastal and Open Ocean Networks"), a result of this separation has been a gap in spatial coverage between the near coast and the open ocean, with a particular lack of observations over the shelf break and continental shelf.

New platforms, such as gliders, HF Radar, and FerryBox systems, as well as increasing efforts to integrate coastal observatories (globally, as with the Pole-to-Pole[64] initiative of MBON, and with the open ocean) are bridging this gap, overcoming the considerable differences in the user needs and in monitoring realities between the open ocean and the coastal region. The coastal region has, for example:

- shallower depth (creating more stress, shear, and mixing)
- smaller typical length scales for phenomena (0-10 km compared to 20-100 km for the open ocean)
- smaller time scales (requiring faster sensors and higher-frequency sampling)
- larger signal ranges (requiring more sensitive sensors in the open ocean)
- increased biological activity (impacting, for example, biofouling)
- additional EOVs at the coast, including turbidity
- higher economical activity (leading to more damages to monitoring equipment)

Differences in technology readiness level, data availability, harmonisation level, sampling efficiency (e.g., spatial coverage), and overall objectives must be considered when performing gap analyses and critical assessments of coastal and open ocean observing systems and how observational sampling strategies and data management can be integrated across the transition region from open ocean to nearshore. At the same time, the coastal and open ocean observing communities can learn from each other in optimising their networks. For example, the coastal ocean community can benefit

- in harmonisation from the more-advanced state of best practices for common platforms and EOVs in the open ocean
- in readiness development by adapting technologies adapted for the deep ocean for use in coastal applications (e.g., COSTOF2[65], a data communication and backup tool which can manage significant digital data streams from a variety of sensors while consuming very little power)
- in data availability from internationally coordinated data infrastructures
- in promoting sustainability by utilising the open ocean's common interfaces at the international level to connect with other coastal observing systems

In turn, coastal observatories can benefit the open ocean community

- in harmonisation by providing early best practices for new technologies (e.g., in-situ flow cytometry)
- in readiness development by providing test sites on near coast stations
- in data availability by providing a framework to develop and test new portals, as coastal data provide a wider diversity of parameters but with smaller volume
- in sustainability, by linking with higher-profile user needs

[63] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D4.5.pdf
[64] http://www.marinebon.org/pole-to-pole.html
[65] https://www.oceannews.com/news/subsea-intervention-survey/costof2-synchronizes-submarine-observatory-sensors

There are also mutual benefits in numerical modelling, where coastal data can be used to improve and constrain models, leading to improved reanalysis and forecasts, as well as better boundary conditions for coastal models. These numerical models can also be used to help design in-situ coastal observing systems, through OSEs and OSSEs.

AtlantOS Deliverable 4.5[66] ("Gap Analysis of Links Between Coastal and Open Ocean Networks") also makes a number of recommendations on how the gaps between open-ocean and coastal observatories can be overcome to benefit both communities, as well as end-users. Accomplishing these goals will require considerable learning and discussion, and common approaches, where possible, to infrastructure, sampling protocols, data, and provision of services. GOOS should establish a regular process to facilitate communication between leading proponents of the coastal and open-ocean observing networks to encourage harmonised network planning, shared infrastructure, data integration, common best practices, and a united approach to applications and seeking financial support.

3.3 Data Management

The AtlantOS project, recognising the importance of data management in the ocean information value chain, established Work Package 7 (Data Flow and Data Integration) to provide leadership for Europe in implementing GEOSS (Global Earth Observation System of Systems[67]), integrate standardised in-situ key marine observations, and improve the use of ocean information to make better decisions and policies. AtlantOS Deliverable 7.1[68] ("Data Harmonisation Report") identified a number of ways in which to improve data harmonisation, including interoperability (i.e., common data standards, including identifiers for platforms, common vocabularies, and DOI citations), regulations on open access, prioritisation of EOVs, and connection with and use of GEOSS services.

As described in AtlantOS Deliverable 7.7[69] ("Atlantic Ocean Data Integration"), while Europe and North America [and Australia] possess advanced infrastructures for the collection, archiving and dissemination of Atlantic Ocean data, other regions do not: Southern Africa has established some systems to collect, archive and disseminate data, but they are lacking in Northern Africa, and although there are multiple organisations in South America concerned with data management, open data sharing has not gained wide acceptance. The report highlighted three key areas in which improved collaboration could have a significant impact on data integration: 1) quality assurance and quality control, 2) data standardisation, and 3) interoperability, semantics and machine learning. Working groups were established for each, which came up with recommendations touching on how to overcome restrictions in sharing arising from: quality concerns, the desire to secure first priority to publish, inadequate traceability of data sources (i.e., making citation difficult), and concerns regarding misinterpretation and misuse of the data.

Deliverable 10.5[70] ("Best Practices in Stakeholder Engagement, Data Dissemination and Exploitation") notes that data portals are "a key tool to interact with stakeholders and as a gateway to disseminate, and facilitate the exploitation of data and other outputs from ocean observatories", that one of the attributes such a portal must have is data availability, and that user engagement is critical to building and refining data access.

The specific recommendations and actions from these reports on data standards and data management will not be repeated here, except to reiterate that data gaps are one of the four types of gaps in the ocean information value chain, and perhaps the easiest to rectify. A well-functioning data system that easily and

[66] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D4.5.pdf
[67] https://www.earthobservations.org/geoss.php
[68] https://www.atlantos-h2020.eu/download/deliverables/7.1%20Data%20Harmonization%20Report.pdf
[69] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D7.7.pdf
[70] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D10.5.pdf

freely provides data to scientists, third-party application developers, and end-users is the critical conduit from data providers to information users, without which there is no real purpose to invest in ocean observations.

Beyond users of ocean information, however, proper management of data and metadata enables providers of ocean data, including network proponents, to make the observing system more effective and efficient. Sharing infrastructure, for example, necessitates that observers are familiar with upcoming cruises and deployments – what platforms, sensors, and sampling protocols are planned, and where. This knowledge can also better inform future expansion plans. The proper use of data in assessments and applications is also predicated on understanding which quality control and analysis techniques have been used on the data.

Optimising the observation system and getting the full value out of the resulting data thus requires the proper management of data and metadata, including planned deployments, best practices, and quality control. Proper attribution of the data in applications and assessments will also raise the visibility and importance of the underlying data, improving sustainability.

3.4 Monitoring the Observation System

Work Package 9 (System evaluation and sustainability) of AtlantOS is concerned with evaluation and sustainability of the ocean observing system. Task 9.2 (Adequacy of ocean information for stakeholders and EOVs) piloted a national survey asking about ocean observing activity and ocean information priorities in five countries. The report (Deliverable 9.4[71] – “Report on the performance of AtlantOS observing system”) noted that no one group within a nation typically is aware of the myriad observing activities that different ministries, agencies, and academic institutions carry out, but that they realise such a consolidated view is important. This knowledge would also help data providers, application developers, and end users, as noted in the previous section. The survey of national priorities is also helpful, both in assessing whether the current observing system meets user needs and in prompting observers to consider how they might fill these gaps. The report provided a number of recommendations related to GOOS focal points, regular national assessments of priorities, open data, and funding.

Assessing how the observation system is performing on shorter timescales requires knowledge of how infrastructure is currently being used – up-to-date metadata on deployments, activity, data return rates, and data quality. Two initiatives (from JCOMMOPS and from EMODnet, as described in AtlantOS Deliverable 9.3[72] (“Report on assessment of the performance of AtlantOS observing system”) within Task 9.1 (System monitoring/evaluation), developed systems to monitor, in near-real time for platforms that provide their data in that manner, ocean observing activity; some networks provide data post-cruise, but many are not yet part of the monitoring process.

The JCOMMOPS monitoring tool (see AtlantOS Deliverable 9.1[73] - “Web based monitoring tool of the Atlantic Ocean observing system, international”) focuses on international efforts in the Atlantic Ocean. It provides a real-time monitoring dashboard, dedicated monthly monitoring maps, interactive maps, performance indicators, and various statistic and monitoring tools, all of which are exportable, customizable, and embeddable. It presently monitors Argo profiling floats, the DBCP surface drifters, the OceanSITES moorings

[71] https://www.atlantos-h2020.eu/download/deliverables/D9.4_Report%20on%20the%20performance%20of%20AtlantOS%20observing%20system_final.pdf
[72] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D9_3.pdf
[73] https://www.atlantos-h2020.eu/download/deliverables/9.1%20Web%20based%20monitoring%20tool%20of%20the%20Atlantic%20ocean%20observing%20system.pdf

time-series, the GO-SHIP hydrographic reference lines, the SOT met/ocean ship based observations, and the GLOSS sea level tide gauges. Ocean gliders, marine mammals, and HF radar systems are being added.

The EMODnet monitoring tool (see AtlantOS Deliverable 9.1[74] - "Web based monitoring tool of the Atlantic Ocean observing system, Europe") focuses on the European contributions to monitoring in the Atlantic Ocean; the dashboard allows users to view and export various statistics about the data portal content and usage, including measures presenting how much data and how many platforms are made available on a daily basis, and extracts statistics on page access and data downloads, etc. The tool monitors fixed and moving platforms such as fixed stations, mooring buoys, tide gauges, surface drifters, Ferryboxes, Argo floats, gliders, marine mammals and HF radars.

In each case, functionality will continue to be enhanced after the AtlantOS project ends, with new networks being added, and additional statistics. There are two areas, in particular, that need to be improved: the inclusion of more biogeochemical and ecosystem networks, and a move from regional platform-based measures (e.g., the number of Argo profilers) to more sophisticated local (e.g., in specific areas of concern) measures and EOV- and phenomenon-based metrics. The former will give a more balanced view of the state of ocean observation, while the latter will enable us to monitor how well the system is meeting the needs of the users (i.e., for integrated information) irrespective of the observation network(s) supplying the data. Establishing integrated metrics, however, requires a level of standardisation in the use of EOVs and phenomena that has only recently been sufficiently reached.

Recommendations from Deliverable 9.3[75] ("Report on assessment of the performance of AtlantOS observing system"), the summary report for Task 9.1 (System monitoring/evaluation), include clearly defining SMART (specific, measurable, achievable, relevant, and time-based) targets when designing network operations; working with JCOMMOPS and EMODnet to regularly evaluate and update metrics (including EOV- and phenomenon-based metrics); providing free and open data; providing activity-related metadata to JCOMMOPS and EMODnet to enable performance monitoring; and providing cruise and deployment plans as early as possible to facilitate network integration.

In particular, JCOMMOPS and EMODnet have noted that there are two key requirements for proper performance monitoring: 1) a network design and implementation plan that includes SMART global, regional, and (where applicable) localised measures, and 2) metadata registration. Unfortunately, very few networks are yet at this stage; the Argo program, which was designed with specific scientific objectives, is likely the closest, and it is already possible to begin to 'micro-manage' this network (e.g., direct more new deployments to particular locations) to benefit its objectives.

SMART EOV- or phenomenon-based metrics can be established only after a critical number of individual networks have developed their individual objectives and regularly provide the relevant metadata. Once this gold standard is reached, networks can work together with data integrators such as JCOMMOPS and EMODnet to optimally monitor the network to ensure it meets the needs of its users.

3.5 Models and Forecast Systems

Numerical models are used to predict future conditions in the atmosphere and in the ocean; although atmospheric forecasts are more widely known, and relied upon, by citizens, ocean forecasts are critical for marine shipping, industrial activities (e.g., offshore oil and gas), coastal protection and disaster risk reduction authorities, and a wide variety of other users. Models also create longer-term projections to examine, for

[74] https://www.atlantos-h2020.eu/download/deliverables/9.2%20Web-based%20monitoring%20tool%20of%20the%20Atlantic%20Ocean%20observing%20system.pdf
[75] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D9_3.pdf

example, how different carbon-reduction scenarios will affect the oceans in the future. However, these models can also be used to estimate current ocean conditions in regions where there are no observations (nowcasts) or to estimate ocean conditions in the recent or ancient past (hindcasts). In each of these cases, the assimilation of ocean data into the model is critical to initialise and constrain the model results, decreasing the error and uncertainty.

Whereas hindcasts rely on quality-controlled delayed-mode data, nowcasts and forecasts require real-time and near real-time data, and an entire operational system (including the Global Telecommunication System, or GTS[76]) has evolved to provide the latest data with some degree of quality assurance and control. Satellite observations provide synoptic data over large areas of the ocean surface, but interior measurements are also critical; the Argo program, for example, led to a major improvement in modelling. In-situ measurements are also helpful in calibrating and validating satellite observations. At present, data assimilation focuses mainly on physical variables, including temperature, salinity, and sea-level height. Biogeochemical and biological data will become more important in the future, particularly as these data are less sparse and more constant in time and with the further integration of chemistry and biology forecast systems.

Numerical models can be used to determine the types of data, and the observation locations, that have the greatest impact on reducing model error and uncertainty (i.e., in constraining models) or understanding phenomenon targeted by observing networks (e.g., locations and depths of largest gradients or temporal variability). These models, then, can be used as one tool to help optimise the observing network to create a more effective and efficient ocean information value chain. In Task 1.3 (Observing System Design Studies) of AtlantOS, Observing System Simulations Experiments (OSSEs) were used to compare model results (i.e., ocean state) between runs with full data assimilation (the “nature run”) and those in which some data was removed (to simulate a missing network) or added (to simulate an additional or enhanced observing activity).

AtlantOS Deliverable 1.5[77] (“Synthesis of OSSE results”) described the physical and biogeochemical OSSEs and the statistical techniques for ocean carbon and climate prediction, as well as the experiment results. The report noted that the assimilation of biogeochemical and biological data is at a much earlier stage of development than for physical data, but that a number of data assimilation techniques were developed for the former, and that the AtlantOS effort was the first time a coordinated system of inter-comparison OSSEs was performed for physical variables. Results indicate that (in the first results of OSSEs with biogeochemical data) BGC Argo is having a positive impact, that Deep Argo will need to reach 6000m in specific regions, and that continuity of the observing system backbone is key.

AtlantOS Deliverable 1.6[78] (“Model guidance for the evolution of the Atlantic Ocean Observing System”) further explored the recommendations from the OSSEs on the ocean observing system, on individual observing networks (e.g., increased Argo activity in western boundary currents and along the equator would improve estimates of T and S for the entire Atlantic, particularly between 300m and 2000m depths), and on future observing design activities and OSSEs (including newly developed statistical or data assimilation techniques and those still needed). In particular, the report noted that OSSEs require heavy and dedicated infrastructures running Research and Development versions of operational ocean analysis and forecasting systems, and that these activities should be consolidated and developed in Europe as part of a partnership between EOOS (the European Ocean Observing System) and the Copernicus Marine Service, in cooperation with international partners such as OceanPredict.

It is important to be aware of the technical limitations of OSSEs, and to acknowledge that the information resulting from them is only one of many considerations (e.g., political, financial, and feasibility) impacting

[76] http://www.wmo.int/pages/prog/www/TEM/GTS/index_en.html
[77] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D1.5.pdf
[78] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D1.6.pdf

decisions on how to organise and optimise ocean observation systems. Nevertheless, it will be important to mount a coordinated and recurring international OSSE inter-comparison effort to benefit ocean observing system design, as was done for climate projections (and regularly featured in reports of the Intergovernmental Panel on Climate Change – see for example Chapter 9[79] of the "Contribution of Working Group 1 to the Fifth Assessment Report of the IPCC"[80]). Systematic inter-comparisons will require dedicated infrastructure; coordination between different models; dialogue between modellers, data assimilation experts, and observation experts to properly design studies; and coordination from Copernicus Marine Services and EOOS with international partners. AtlantOS partners will addressing these issues at the upcoming OceanPredict and OceanObs'19 conferences.

3.6 Governance and Partnerships

Ocean information useful to end-users results from ocean observations of many types from different sensors and networks in different regions of the Atlantic Ocean being quality-controlled and archived in free and open databases, integrated and analysed in different ways, and assimilated into numerical models and supported by results from models. There is a need for best practices, standards, and an understanding of capacities and limitations at each stage of the ocean information value chain. Effectively reaching across disciplines, geography, and components of the ocean observing system requires frameworks, partnerships and a governance model.

Portions of the observing system are at various stages of organisation. The Framework for Ocean Observing, for example, organises observation activity around EOVs, with agreement on biology and ecosystem EOVs a recent achievement. GOOS has physics, biogeochemistry, and biology / ecosystem panels to organise activity within disciplines and to work on integration between them. GOOS GRAs organise ocean observing activity more regionally, with varying levels of success. Within Europe, Copernicus coordinates information services based on satellite and in-situ data. The Committee on Earth Observation Satellites (CEOS[81]) ensures international coordination of satellite-based earth observation. These frameworks and organisations are good building blocks, but a truly integrated fit-for-purpose all-Atlantic Ocean observing system will need to develop additional systems to, for example (and as noted in previous sections), coordinate OSSEs and design experiments, propagate best practices and standards, integrate individual observing networks, solicit regular feedback from nation states on ocean activity and priorities, and create a community of uses, developers, and observers.

AtlantOS has advanced integration in each of these areas, including by initiating discussion among different groups, piloting applications and national surveys, developing frameworks for OSSE experiments, promoting best practices and open data, and monitoring ocean observing activity. However, the AtlantOS project is at its end and other partnerships and governance models must be established to continue this work, as well as to advocate for sustained funding and to work more closely with the satellite observing community. CEOS and its partners, for example are planning major and significant evolutions for the next decade, in improved spatial and temporal resolution and in new variables (e.g., surface currents). This has important implications for the in-situ observing community and its future design, both for validation of satellite data and to complement satellite observations in creating an integrated ocean observing system.

The AtlantOS High-Level Strategy for an All-Atlantic Ocean Observing System outlines a vision of "a comprehensive Atlantic Ocean Observing System that benefits all of us living, working, and relying on the ocean" and describes an integrated concept for a basin-scale partnership to establish a multi-disciplinary fit-for-purpose Atlantic Ocean observing system. It provides opportunity for all countries of the Atlantic to join,

[79] https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter09_FINAL.pdf
[80] https://www.ipcc.ch/report/ar5/wg1/
[81] http://ceos.org/

and outlines how AtlantOS the programme will coordinate (in partnership with GOOS and GEO and in connection with the Galway Statement on Atlantic Ocean Cooperation, the Belém Statement on Atlantic Research and Innovation Cooperation, and the United Nations Decade of Ocean Science for Sustainable Development) the implementation of observing systems and collection of ocean data in the Atlantic.

The European Strategy for All-Atlantic Ocean Observing (Europe's contribution to the AtlantOS High-Level Strategy) outlines a vision that, by 2030, the European component of the All-Atlantic Ocean Observing System will be fully coordinated and fit-for-purpose, with common (i.e., pan-European) strategic priorities, implementation plans, and voluntary commitments. It is more prescriptive on governance, with a key action being to establish a centralised European governance structure within EOOS to coordinate multinational, multi-disciplinary, and multi-institutional contributions.

GOOS also recognises the importance of partnerships and governance in meeting its mission ("To lead the ocean observing community in growing an integrated, responsive and sustained global observing system") and vision to provide one integrated system that can deliver ocean information across three key application areas: climate, operational services, and marine ecosystem health. The GOOS 2030 Strategy outlines three areas of activity (and the Implementation Plan under development will detail specific action items) related to this mission:

1) lead a **hub of cooperation**, providing the global platform through which many different players can coordinate their activities, multiplying individual actions in a systematic way;
2) strengthen the **partnerships for delivery** of ocean information by creating connections across the value chain from observations to end users, enabling feedback and the provision of an efficient system that is truly fit for purpose; and
3) raise the **visibility of the benefits** of ocean observations, energizing funders to support concerted lines of action.

The Atlantic Ocean is bordered by many nations of varying capacity and with different priorities. A nested governance model of multiple overlapping decision-making centres with autonomy choosing to act in cooperation, competition, and conflict resolution is likely the best model for managing an Atlantic Ocean Observing System. Polycentric governance, a model shared by other groups (including GOOS, and GEO) has many advantages, including the capacity to adapt to changing conditions, good fit to institutional needs (e.g., the regional scale is appropriate for some scientific issues, whereas funding is generally on a national level), and a higher capacity to mitigate risk. However, there are a number of important disadvantages, including different levels of accountability and a risk that decisions will not always produce harmonised outcomes. Regular assessments of the performance of the ocean observing system will be key to overcoming these challenges.

4 Conclusions

Ocean observing has progressed greatly in recent years – there is a growing understanding that sound management, policy, and development requires adequate and accurate ocean information, an increasing awareness of the need to properly fund and develop ocean observing programs and analysis systems to obtain ocean data and turn it into useful ocean information, and improved coordination between various ocean observing networks (and with satellite systems) to integrate ocean observing through shared platforms, standards, and best practices, as well as through open data.

However, the need for more accurate and multi-disciplinary ocean information at finer spatial and temporal resolution to inform increasingly complex social issues, the recent rapid development of technology (particularly in the biogenomics realm), and the increasingly difficult funding environment requires even greater integration – the global ocean observation system now needs to move from one where integration is discussed in groups of several networks to one where there is a more organised and coherent plan.

The AtlantOS project has, with partners including the Global Ocean Observing System (GOOS) and the GEO Blue Planet Initiative, worked over the last several years to further integrate existing and more recent ocean observing programs into a more comprehensive and fit-for-purpose Atlantic Ocean observing system, utilizing the Framework for Ocean Observation; ensuring a focus on Essential Ocean Variables; encouraging the collection of compatible metadata; enhancing links between the biological and coastal observation communities; prioritizing free and open access to data; supporting sensor development; and standardizing language and best practices.

AtlantOS has examined user needs, including through pilot projects in WP8 (Societal benefits from observing/information systems) and in national surveys, developed a technology roadmap for near-future ocean observation technologies, produced a cost and feasibility study of present and future ocean observing, and run a series of Observing System Evaluation (OSE) and Observing System Simulation Experiments (OSSE) trials, and developed new ocean simulation techniques to begin to quantify the importance of different ocean observation data types in reducing model error and uncertainty, and improving forecasts.

At a Future Ocean Observing Design Workshop, AtlantOS synthesised these results, along with individual networks' future plans and strategic goals, to envision a future integrated and fit-for-purpose ocean observing system for the Atlantic Ocean. Respecting that funders (generally nation states, but also, increasingly, the private sector) are likely to continue to support certain observing networks to meet national or local needs (or for historical reasons), a number of recommendations are put forth to improve the entire ocean information value chain to meet the needs of society, industry, and the environment. These recommendations touch not only on individual networks, but also on the importance of capacity building and standards in promoting integration.

Recommendation 1: Establish a planned and systematic forum for dialogue between users of ocean information, observation program leaders, and sensor and application developers to understand evolving needs and capacities.

Goals

- Build a strong end-user community aware of the relevance and benefits of long-term ocean observation.
- Build a community of ocean observers aware of user needs so they can refine observation programmes to more efficiently and effectively provide the data needed. This includes better integration between the open ocean and coastal observing communities, as well as between the physics, biogeochemistry, and biology / ecosystem communities.

- Build a community of sensor and technology developers who understand user needs and produce cost-effective monitoring solutions.
- Build a community of third-party application developers to transform ocean data into ocean products and information.

Activities

- GOOS should coordinate this activity internationally; the Physics, Biogeochemistry, and Biology/Ecosystem Panels are already working within the observing community to integrate cross disciplines (e.g., EOVs).
- GOOS GRAs can be valuable in aiding integration between the open-ocean and coastal observation communities. While a number of GRAs are proving to be very effective (e.g., EuroGOOS, IOOS and IMOS), others could use GOOS further support.
- Pilot projects are one method to grow the community of users and application developers.
- GOOS can adopt a regular national survey approach, as piloted in AtlantOS, to understand national needs and priorities.

Recommendation 2: Establish a framework to regularly and systematically evaluate and optimise network design with numerical models (e.g., OSEs and OSSEs) and other analytic tools, including cost and feasibility studies.

Goals

- Identify key locations (e.g., gates or bottlenecks) in which to monitor.
- Prioritise observation requirements relevant to various goals of the observing system (e.g., for science process studies, reducing forecast error, or understanding phenomena and improving applications).
- Demonstrate the importance and value of observations, which will aid in securing sustainable funding.
- Monitor how well the observing system is meeting observation requirements.

Activities

- GOOS and OceanPredict develop long-term strategy and yearly workplans to coordinate international OSE and OSSE simulations.
- Further develop network monitoring tools (such as those created at JCOMMOPS and EMODnet through the AtlantOS project), which include moving beyond platform-based measures to develop EOV- and phenomenon-based metrics.
- Standardise cost-accounting approaches and have GOOS incorporate cost estimates into its regular national survey approach.

Recommendation 3: Establish accessible, discoverable, and interoperable databases for data, metadata (including infrastructure, planned deployments, and current observing activity) and best practices.

Goals

- Ensure all observed data is free and open access, with compatible standards, and associated metadata on quality control, etc.
- Keep current inventories of costly and unique infrastructure and of upcoming deployments, to assist in infrastructure sharing and the development of future enhancements of observation networks.

- Collect an authoritative source of metadata on best practices to help new observation activities establish themselves more quickly and ensure that their data is compatible with the existing system.
- Make available, in near-real time, metadata on current observation activity (i.e., instruments in the water) to allow for monitoring and assessment of how well the observation system is meeting user needs.

Activities

- Resolve the data gap due to unavailable data by encouraging observers to properly fund data management and share data.
- Support efforts to develop, and encourage the use of, data tracking and citation protocols.
- Encourage observation networks to share metadata concerning their available and deployed infrastructure and platforms.
- Support the continued development and sharing of best practices.
- Host regular inter-network dialogue with JCOMMOPS and EMODnet to facilitate the creation and update of EOV- and phenomena-based performance metrics.